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

Plasma Wakefield Acceleration of Charged Particles

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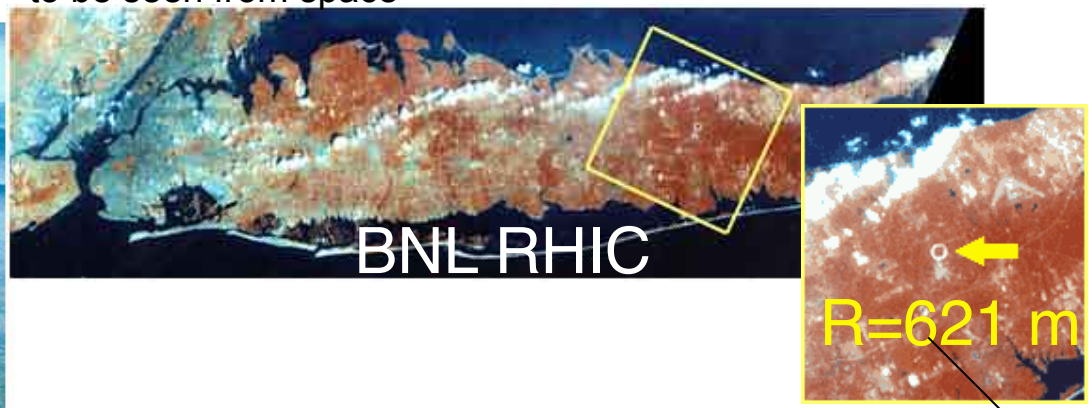
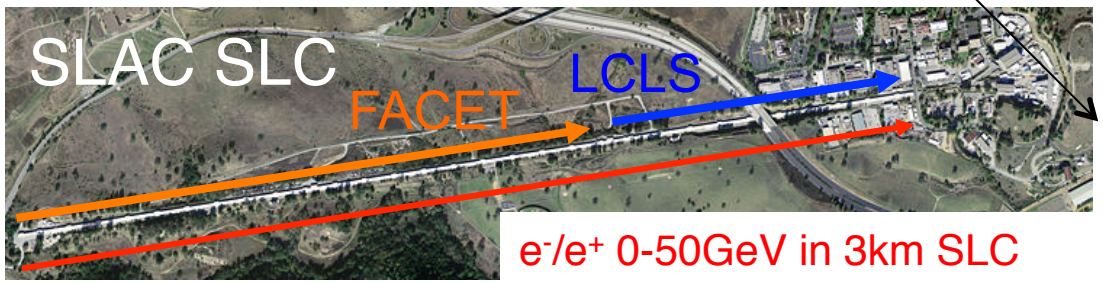
PARTICLE ACCELERATORS

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





e^-/e^+ 0-50GeV in 3km SLC
e^-/e^+ 0-20GeV in 2km FACET
e^- 0-14GeV in 1km LCLS

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

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PARTICLE ACCELERATORS

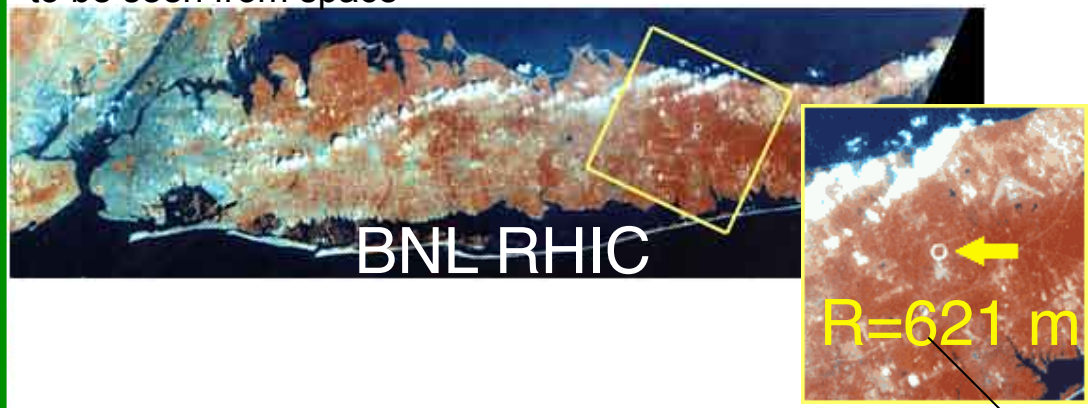
Light particles (e^-/e^+) accelerator
Limited by synchrotron radiation

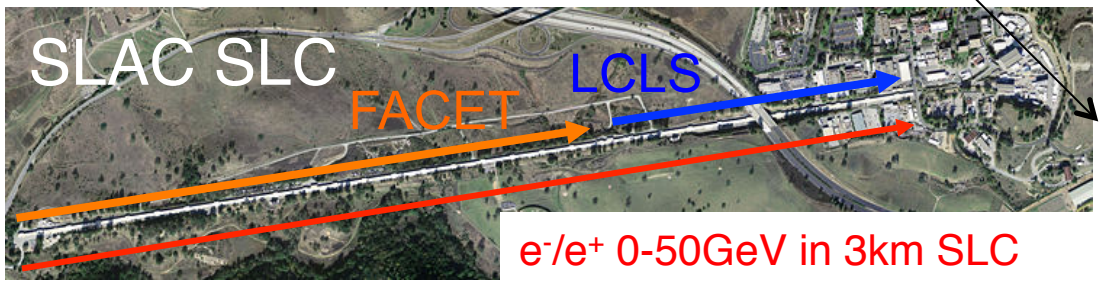
$$P_{synchr} = \frac{e^2}{6\pi\varepsilon_0 c^7}\frac{E^4}{R^2 m^4}$$

Must be linear
But …

$$L = \frac{E(eV)}{G(eV/m)}$$

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





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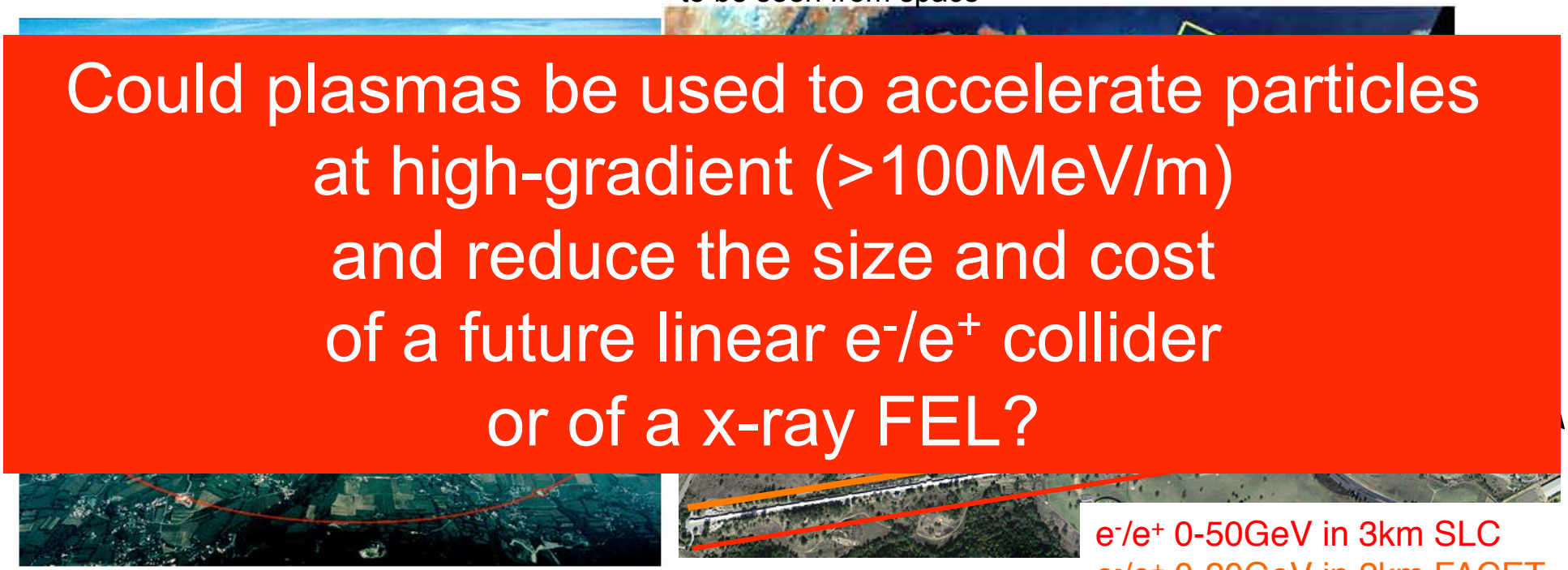

Could plasmas be used to accelerate particles at high-gradient (>100MeV/m) and reduce the size and cost of a future linear e^-/e^+ collider or of a x-ray FEL?

e^-/e^+ 0-50GeV in 3km SLC
e^-/e^+ 0-20GeV in 2km FACET
e^- 0-14GeV in 1km LCLS

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OUTLINE

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

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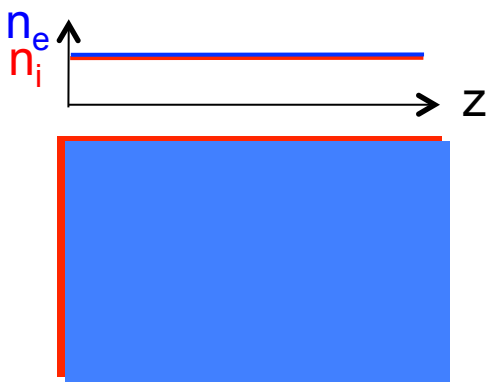
WHY PLASMAS?

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



✧Plasmas wave or wake can be driven by:

- ➢Intense laser pulses (LWFA)
- ➢Dense particle bunch (PWFA)

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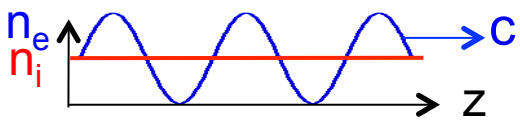
WHY PLASMAS?

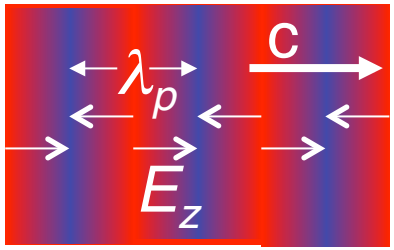
✧Relativistic Electron Electrostatic Plasma Wave (Electrostatic, E_z//k):



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

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

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



LARGE

Collective response!

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

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

Cold Plasma "Wavebreaking" Field

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

✧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)
- ➢Dense particle bunch (PWFA)

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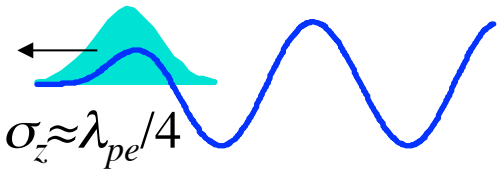
4 PLASMA ACCELERATORS*

- Plasma Wakefield Accelerator (PWFA)

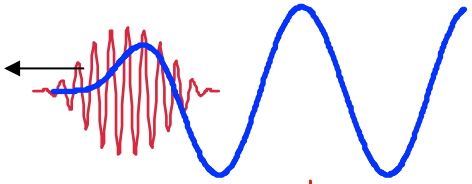
  A high energy particle bunch (e^-, e^+, ...)

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



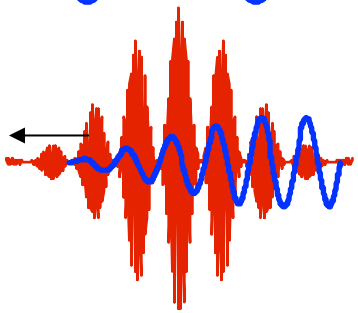
- Laser Wakefield Accelerator (LWFA) *

  A short laser pulse (photons, ponderomotive)



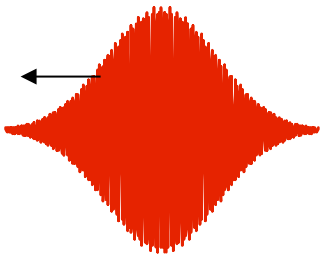
- Plasma Beat Wave Accelerator (PBWA) *

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

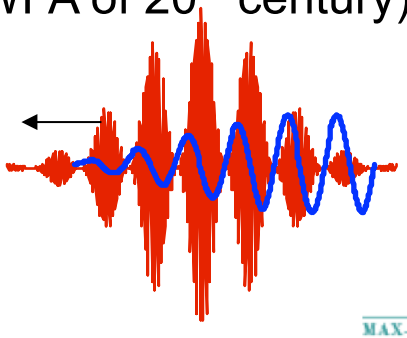


- Self-Modulated Laser Wakefield Accelerator (SMLWFA) *

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



evolves into



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

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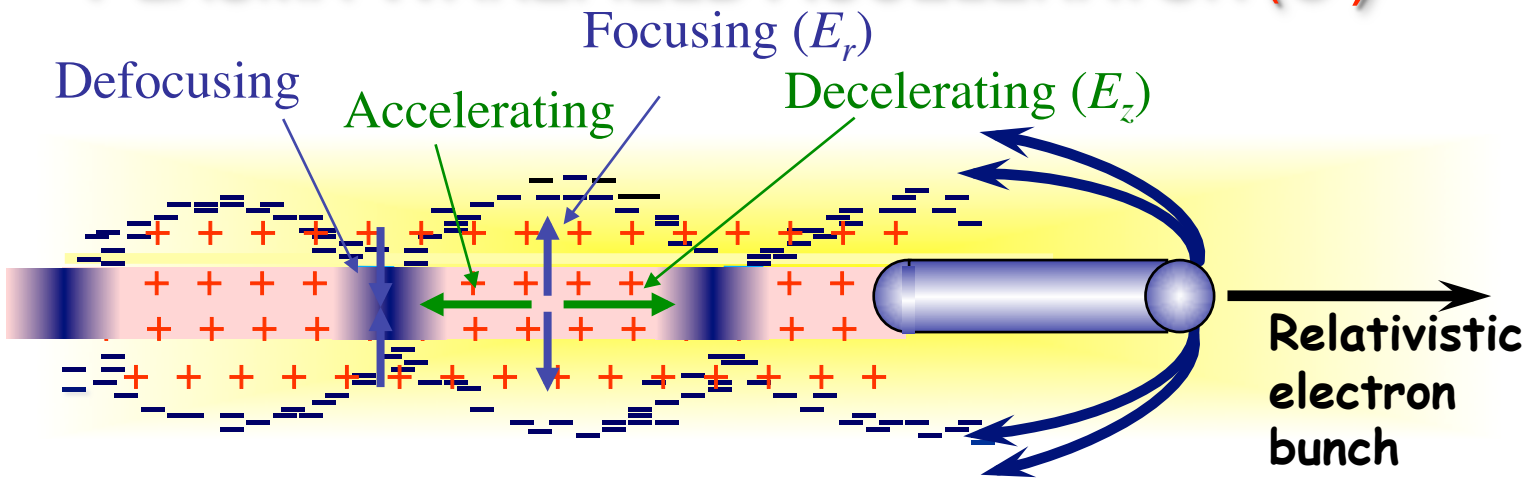
PLASMA WAKEFIELD ACCELERATOR (e^-)



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

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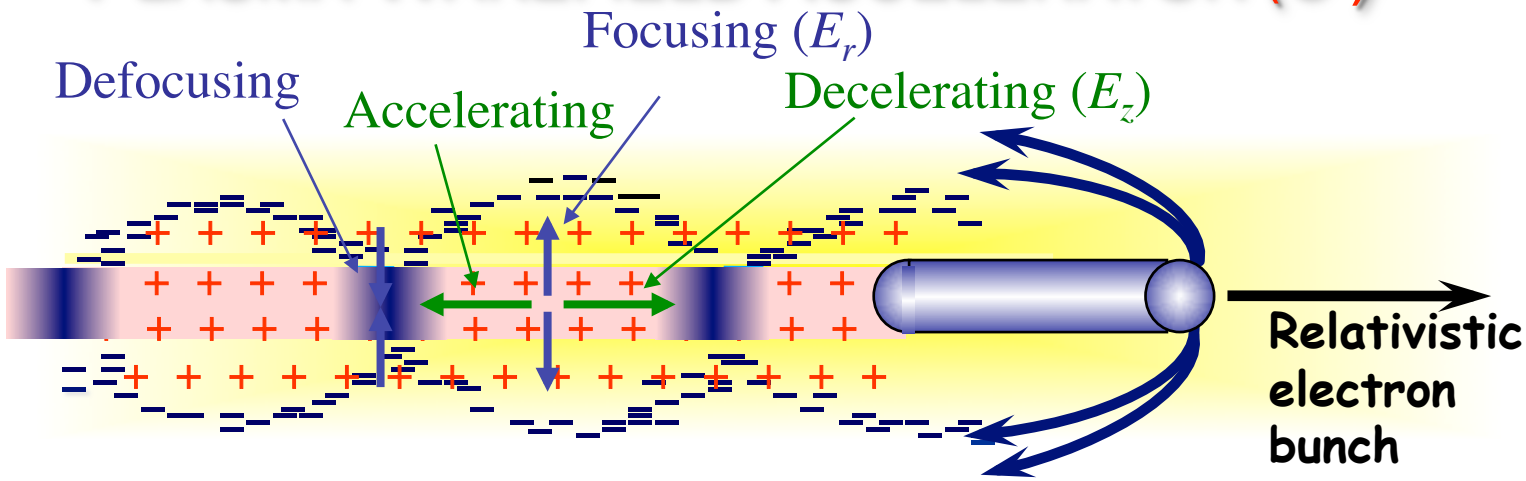
PLASMA WAKEFIELD ACCELERATOR (e^-)



Plasma wave/wake excited by a relativistic particle bunch

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

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

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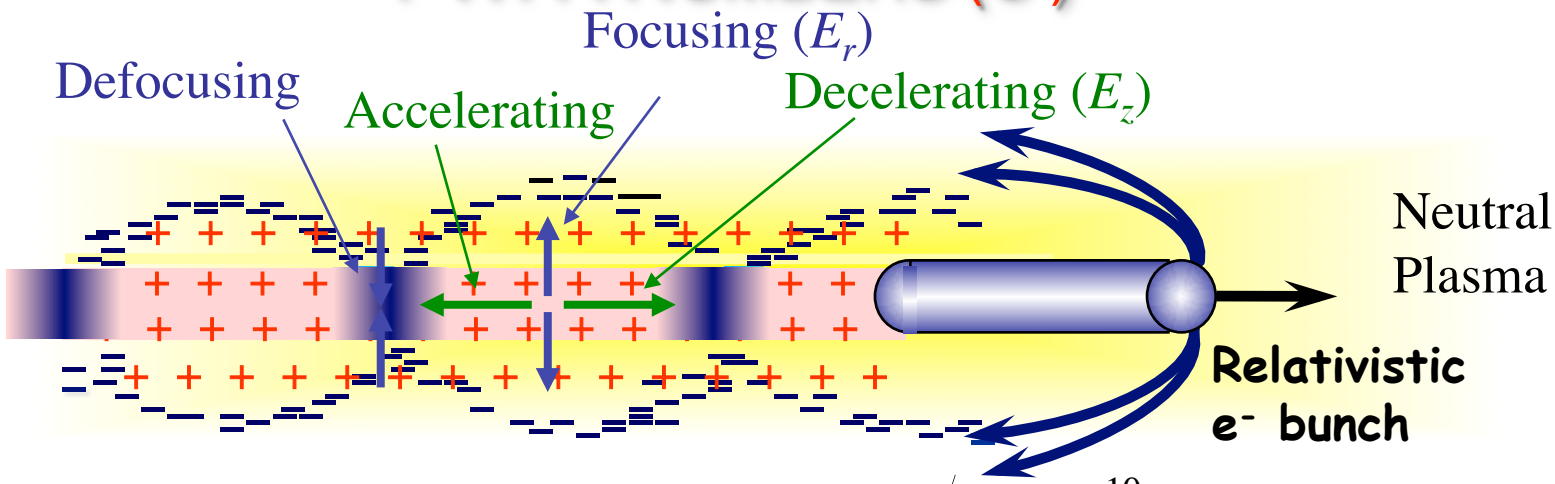
PWFA NUMBERS (e^-)



✧Linear theory (n_b<<n_e) scaling:

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

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

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

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

σ_z= 20 μm, n_e=2x10^{17} cm^{-3}, E_{acc}~ 10 GV/m, B_θ/r=6 MT/m

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

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

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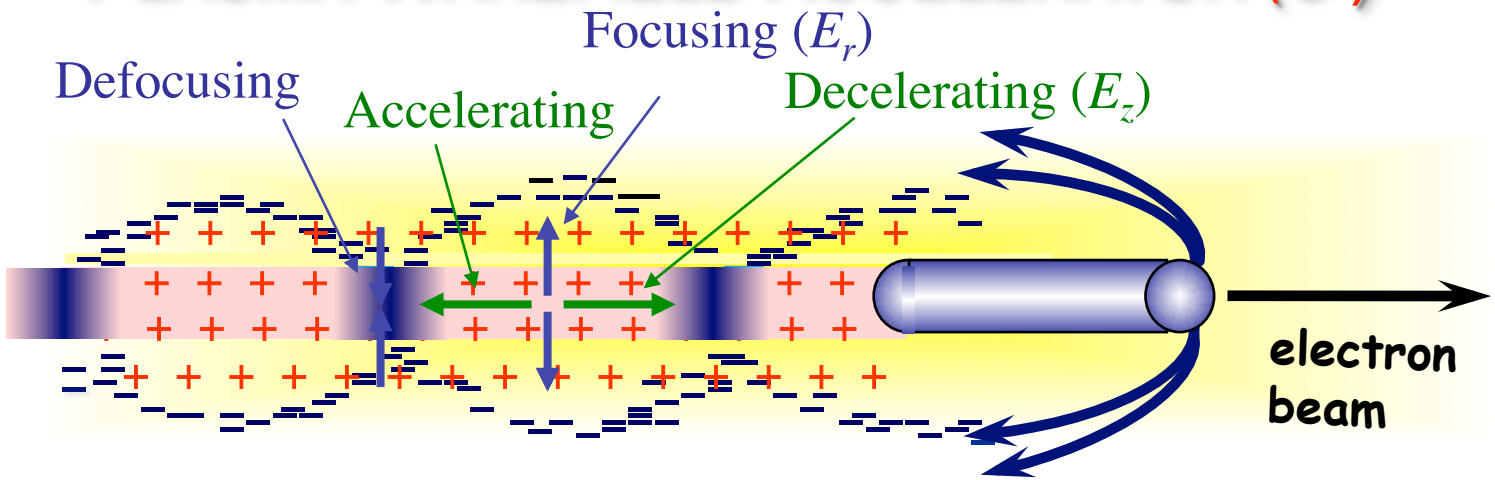
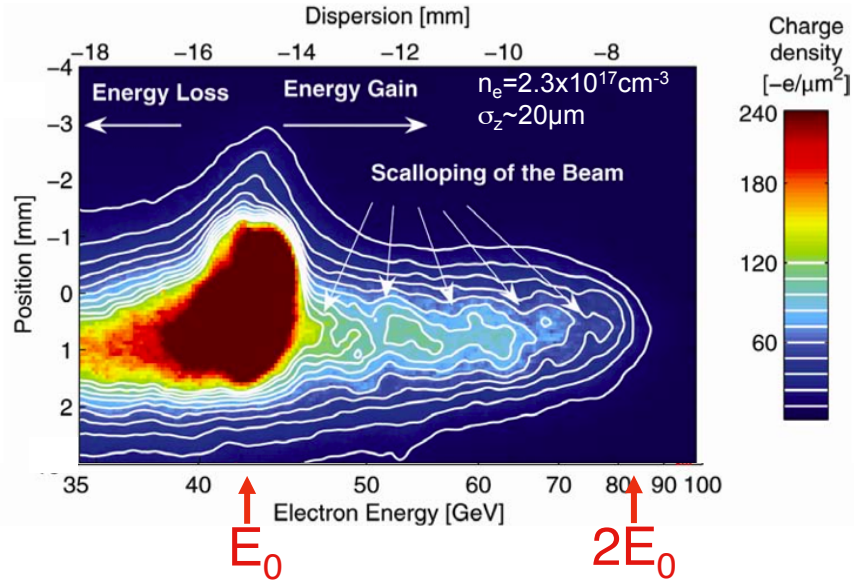
PLASMA WAKEFIELD ACCELERATOR (e^-)



Blumenfeld, Nature 445, 741 (2007)



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

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

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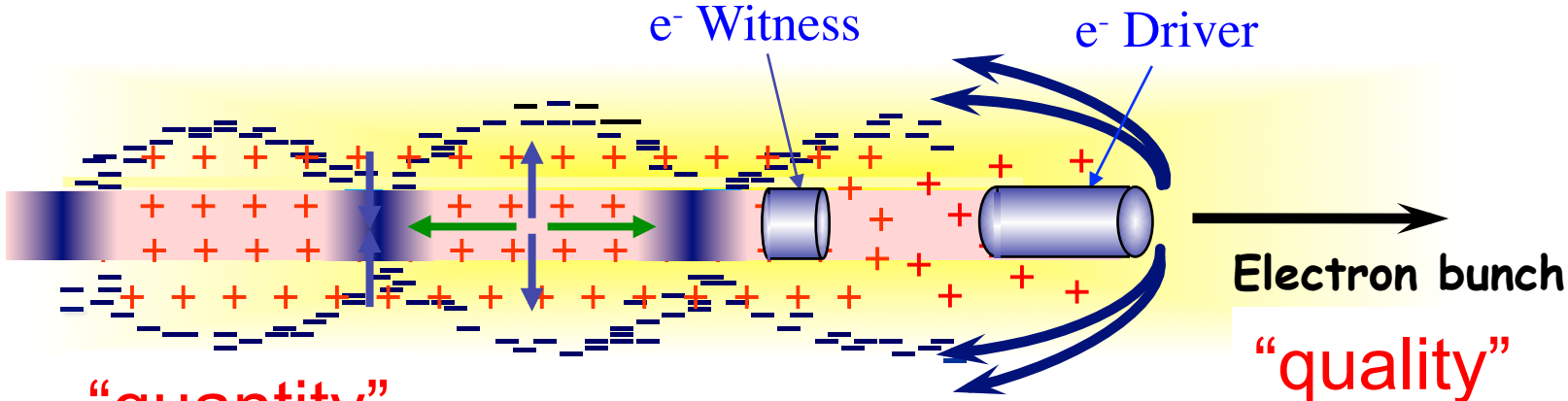
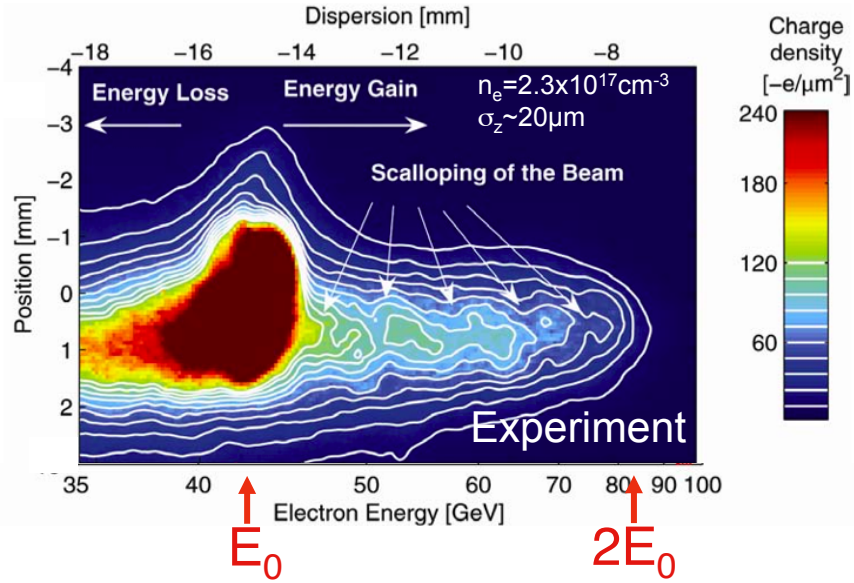
PLASMA WAKEFIELD ACCELERATOR (e^-)



"quantity"

"quality"

Blumenfeld, Nature 445, 741 (2007)



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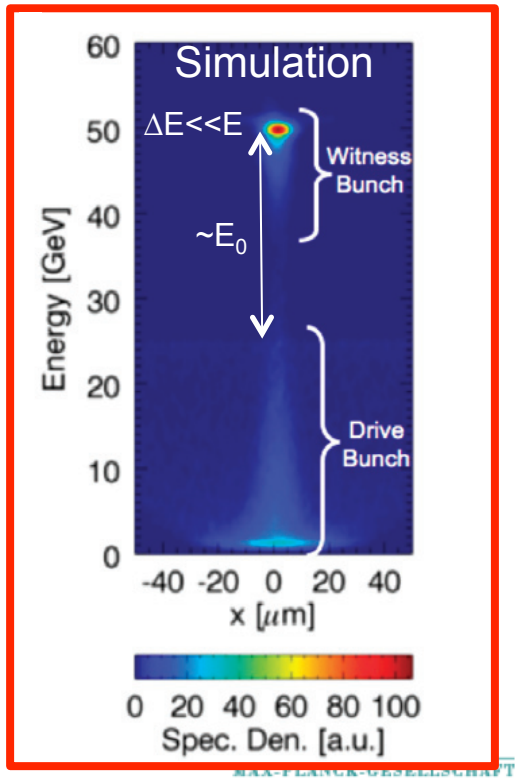
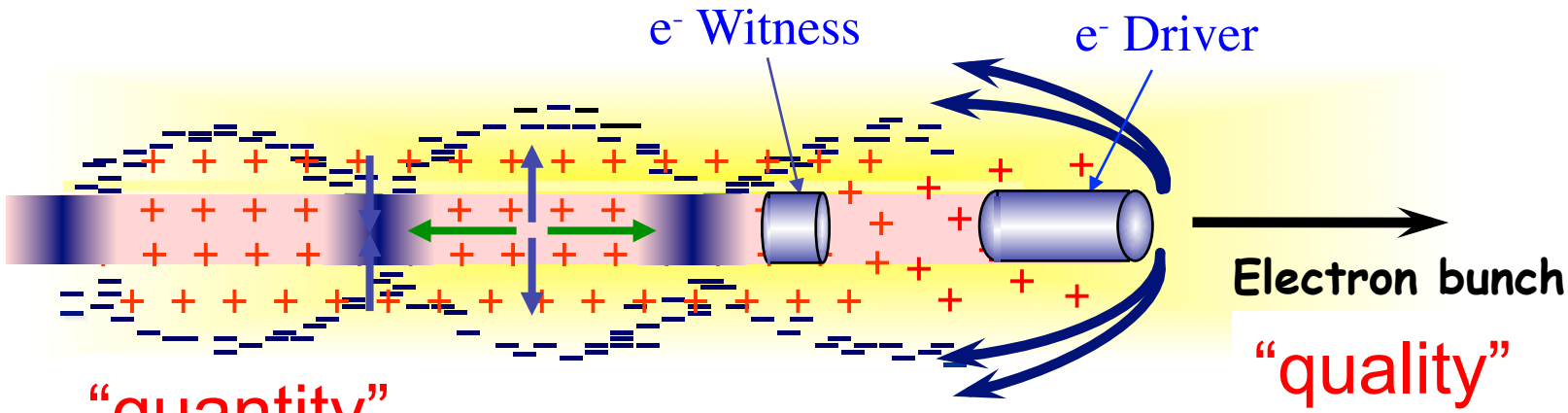
SLAC FACET

E200

Hogan, NJP 12, 055030 (2010)



PLASMA WAKEFIELD ACCELERATOR (e^-)



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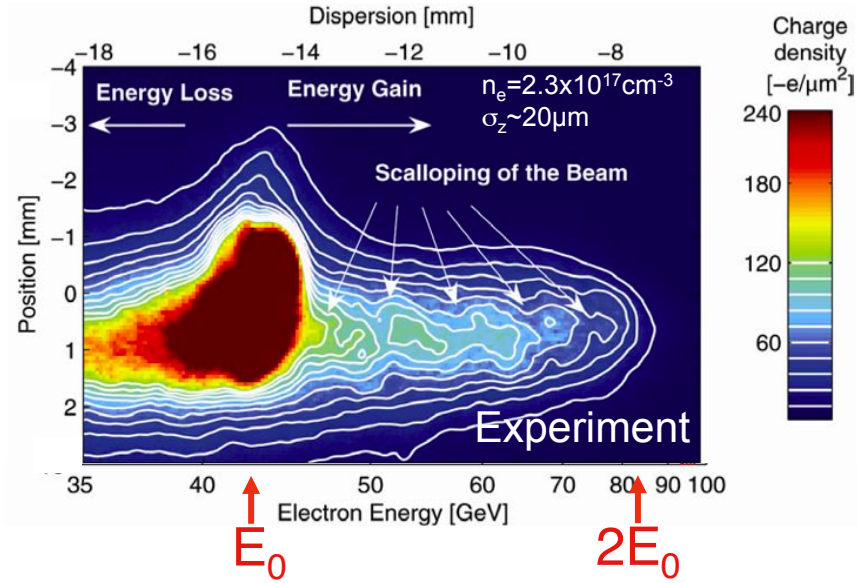
Blumenfeld, Nature 445, 741 (2007)



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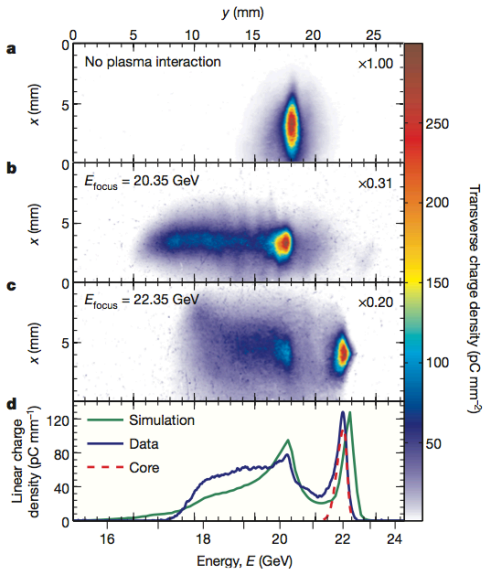
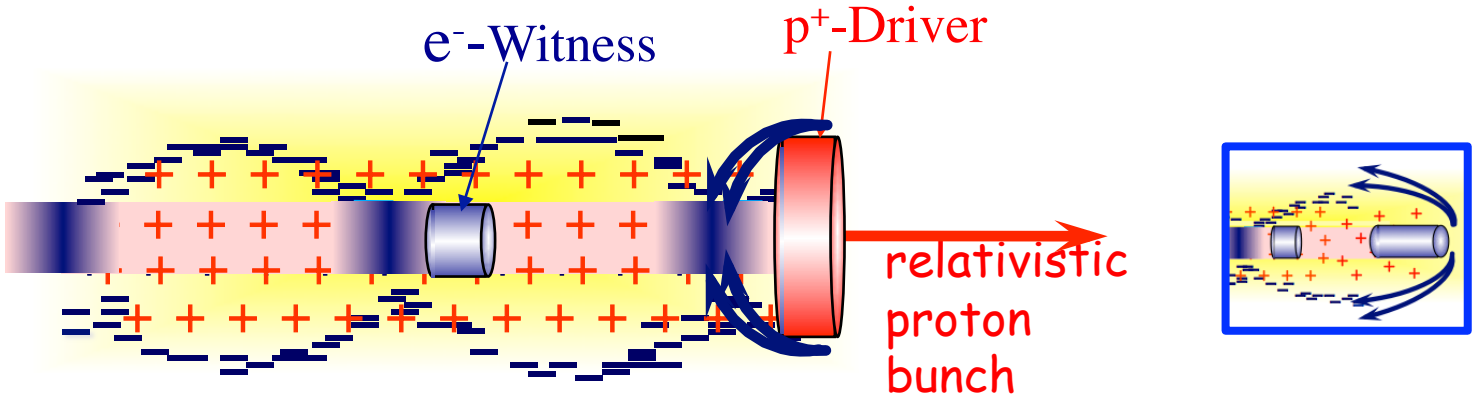
Litos, Nature 515(6) 92 (2014)



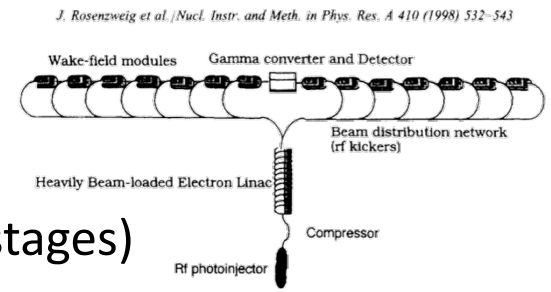
ΔE/E~%

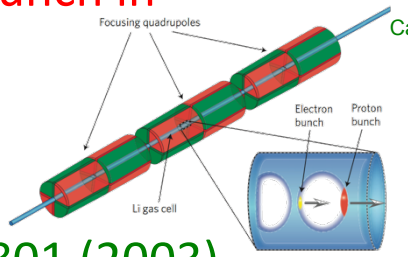
η~30%

p^+-DRIVEN PWFA? YES BUT WHY?



- ✧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 <u>single</u> PWFA stage!
- ✧Large <u>average</u> gradient! (≥1GeV/m, 100's m)
- ✧Wakefields driven by e^+ bunch: Blue, PRL 90, 214801 (2003)

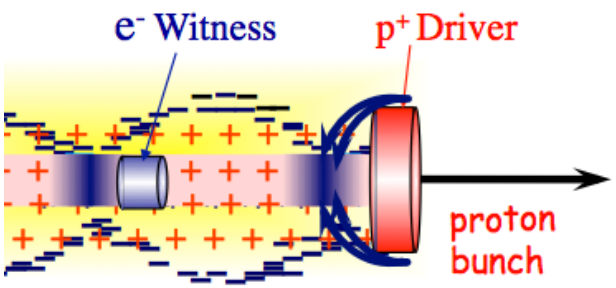


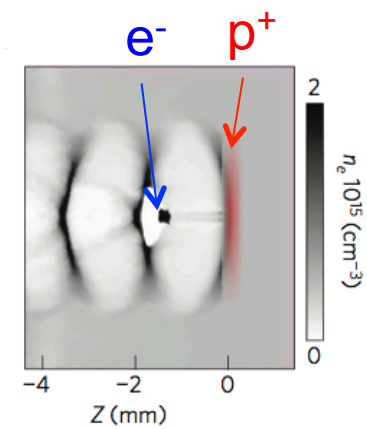


Caldwell, Nat. Phys. 5, 363, (2009)

PROTON-DRIVEN PWFA

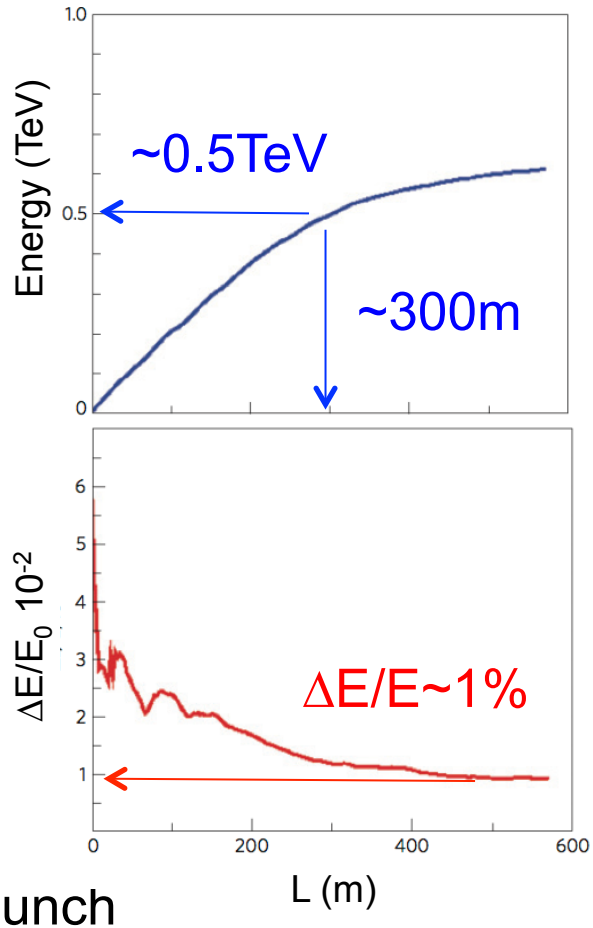
Caldwell, Nat. Phys. 5, 363, (2009)





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

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



- ✧Accelerate an e^- bunch on the wakefields of a p^+ bunch
- ✧Single stage, no gradient dilution
- ✧Gradient ~1 GV/m over 100's m
- ✧Operate at lower n_e (6×10^{14}cm^{-3}), larger $(\lambda_{pe})^3$, easier life …

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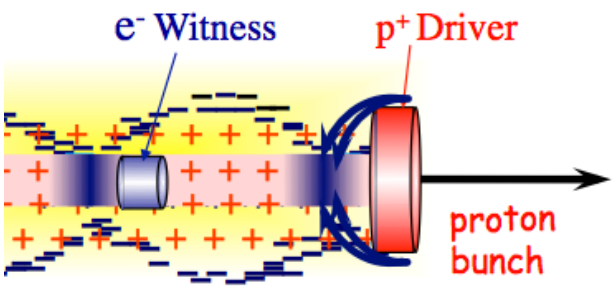
PROTON-DRIVEN PWFA

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

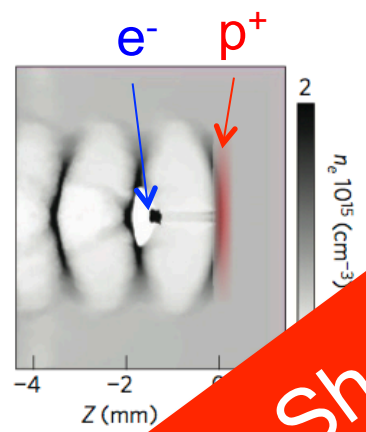


Single Stage

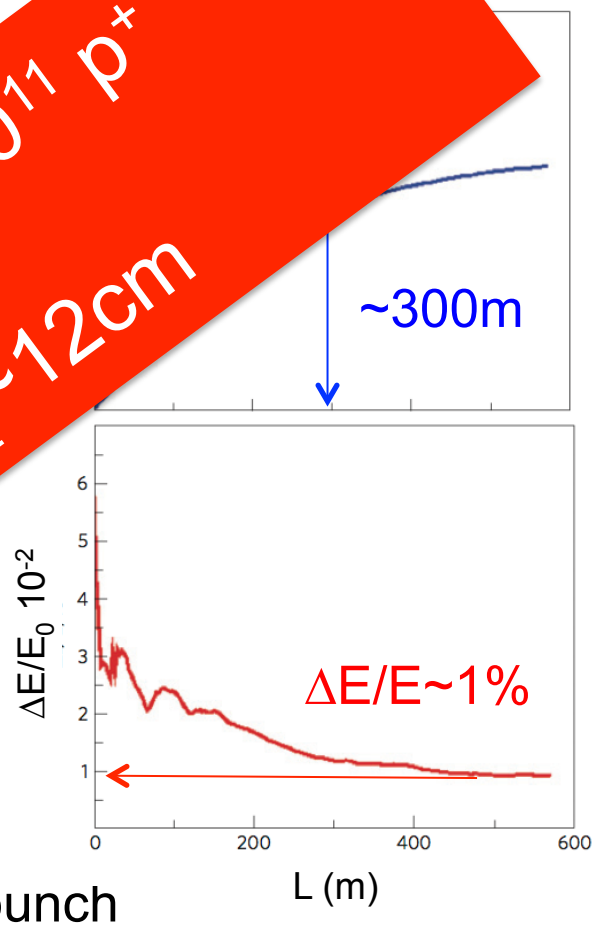
e^-: E_0=10GeV

p^+: E_0=1T

N=10^{10}



		μm
		mrad
	0.43	mm
	1.5×10^{10}	
ε_e	10	GeV
n_p	6×10^{14}	cm^{-3}
λ_p	1.35	mm
	1,000	$T\,m^{-1}$
	0.7	m



Short (100μm) bunches with 10^{11} p^+ do not exist!!! CERN PS-SPS-LHC σ_z~12cm

- ✧ [illegible] the wakefields of a p^+ bunch
- ✧ [illegible] dilent dilution
- ✧ Gr[illegible] m over 100's m
- ✧ Open[illegible] ower n_e ($6\times10^{14}cm^{-3}$), larger $(\lambda_{pe})^3$, easier life …

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- SMI PWFA experiments at CERN with p^+: AWAKE
- Summary

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SELF-MODULATION INSTABILITY (SMI)

- CERN p^+ bunches (PS, SPS, LHC) ~12cm long
- $E_{WB} \sim \omega_{pe} \sim n_e^{1/2}$ and $\sigma_z \sim \lambda_{pe} \sim n_e^{-1/2}$ => $E_{WB} \sim 1/\sigma_z$

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

Self-Modulation Instability of a Long Proton Bunch in Plasmas

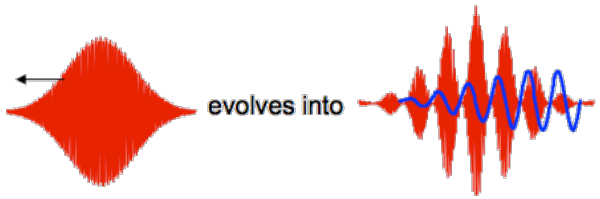
Naveen Kumar* and Alexander Pukhov
Institut für Theoretische Physik I, Heinrich-Heine-Universität, Düsseldorf D-40225 Germany

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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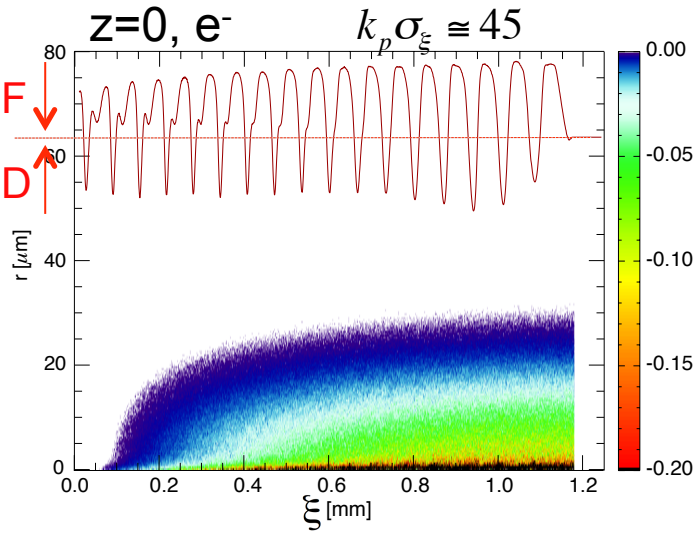
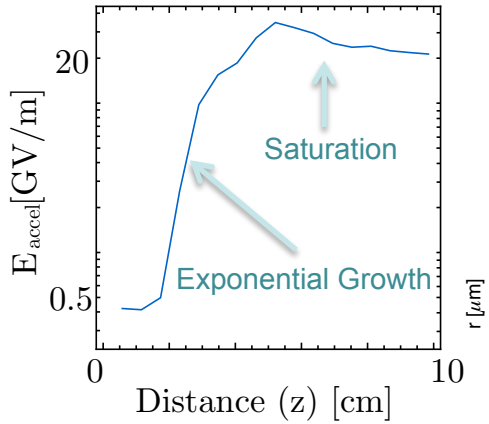
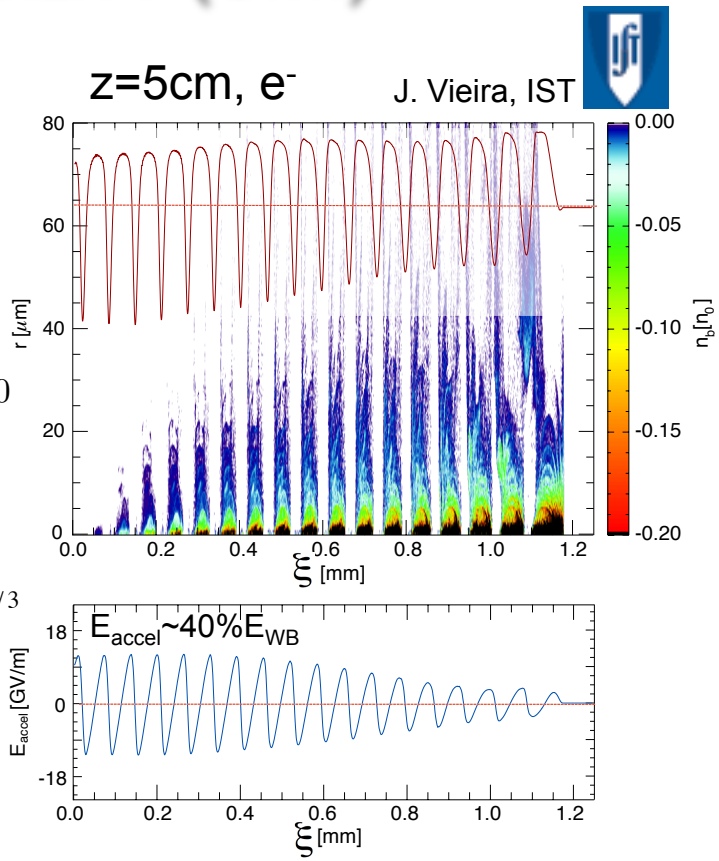
SELF-MODULATION INSTABILITY (SMI)







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

Grows along the bunch & along the plasma

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

- Initial small transverse wakefields modulate the bunch density with ~λ_{pe} period
- Associated longitudinal wakefields reach large amplitude through resonant excitation

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

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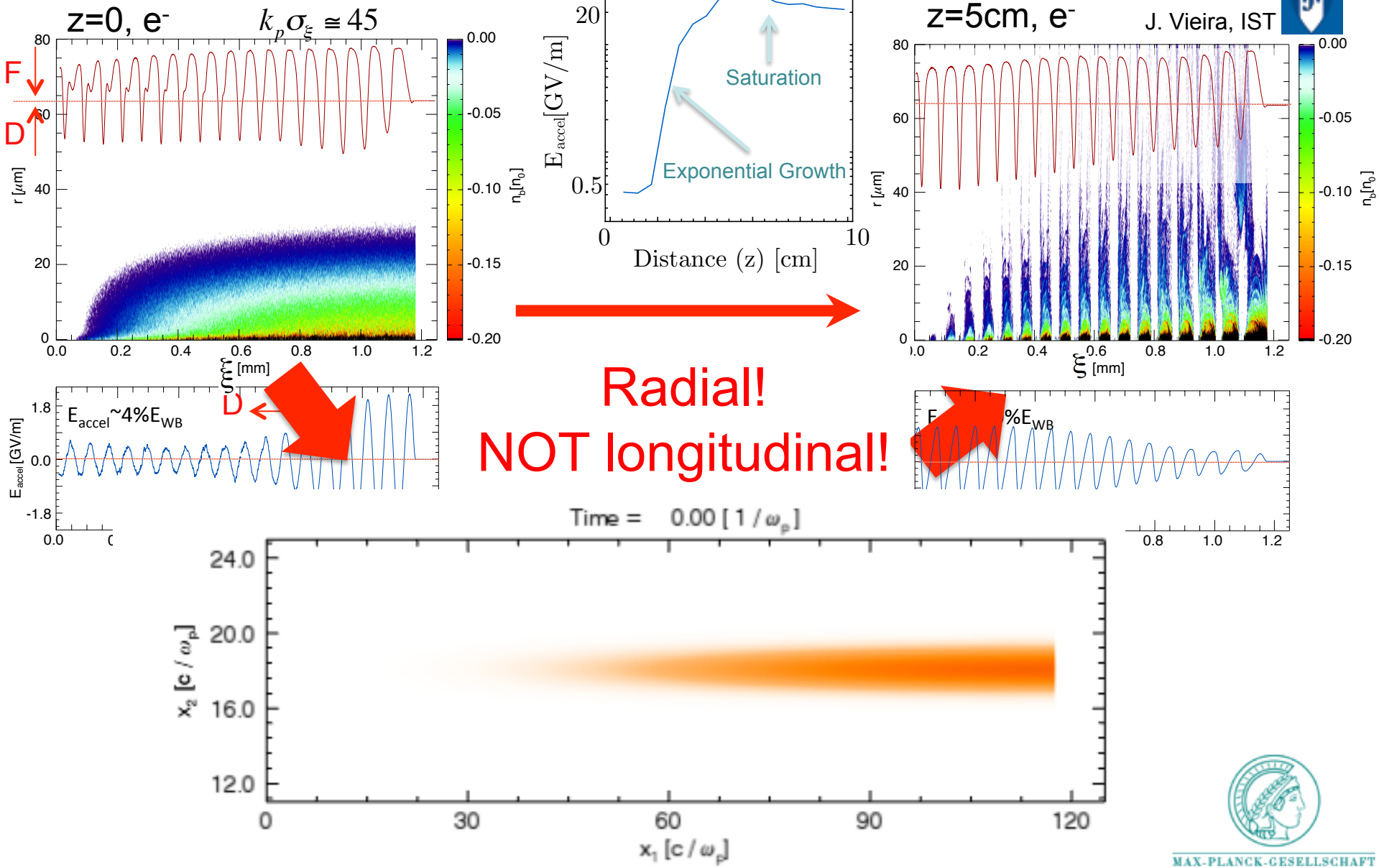
SELF-MODULATION INSTABILITY (SMI)



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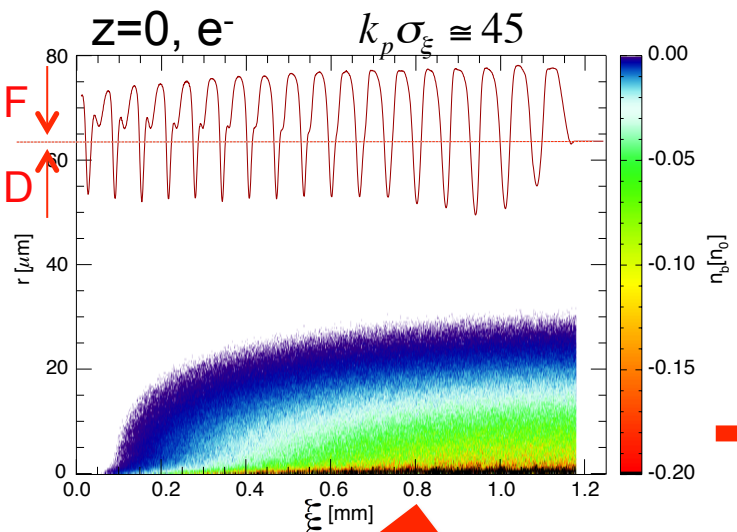
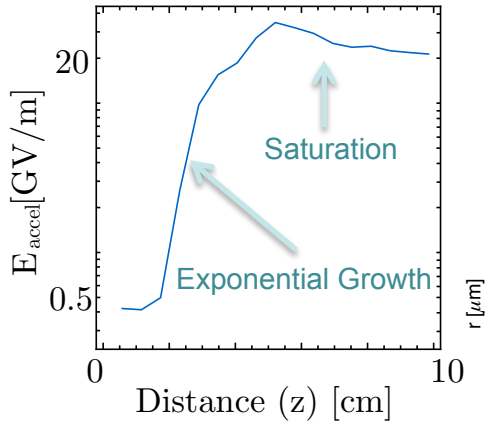
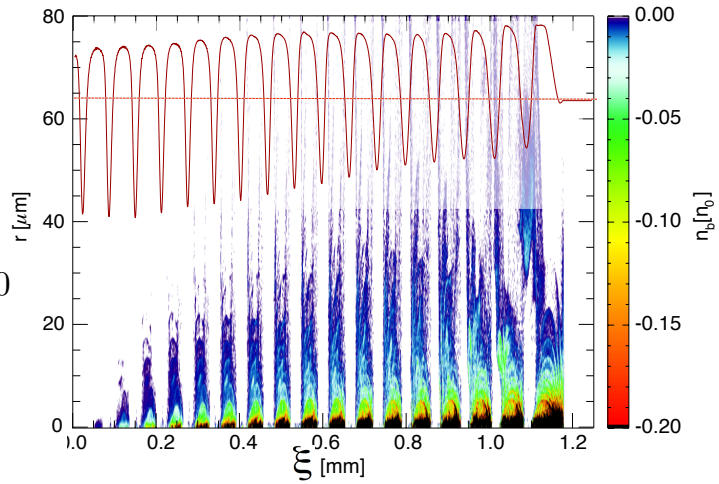
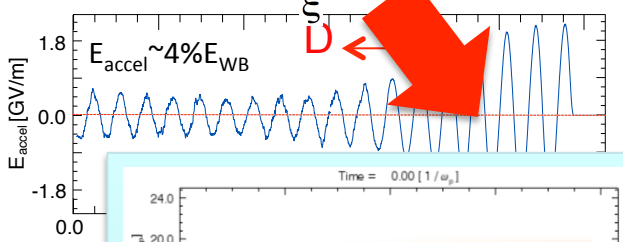
SELF-MODULATION INSTABILITY (SMI)





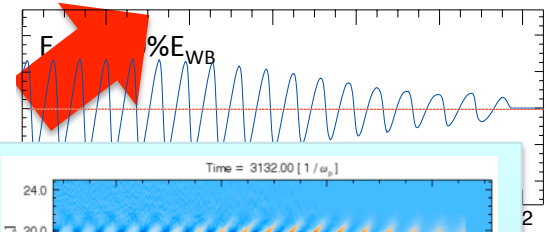
Vieira et al., Phys. Plasmas 19, 063105 (2012).

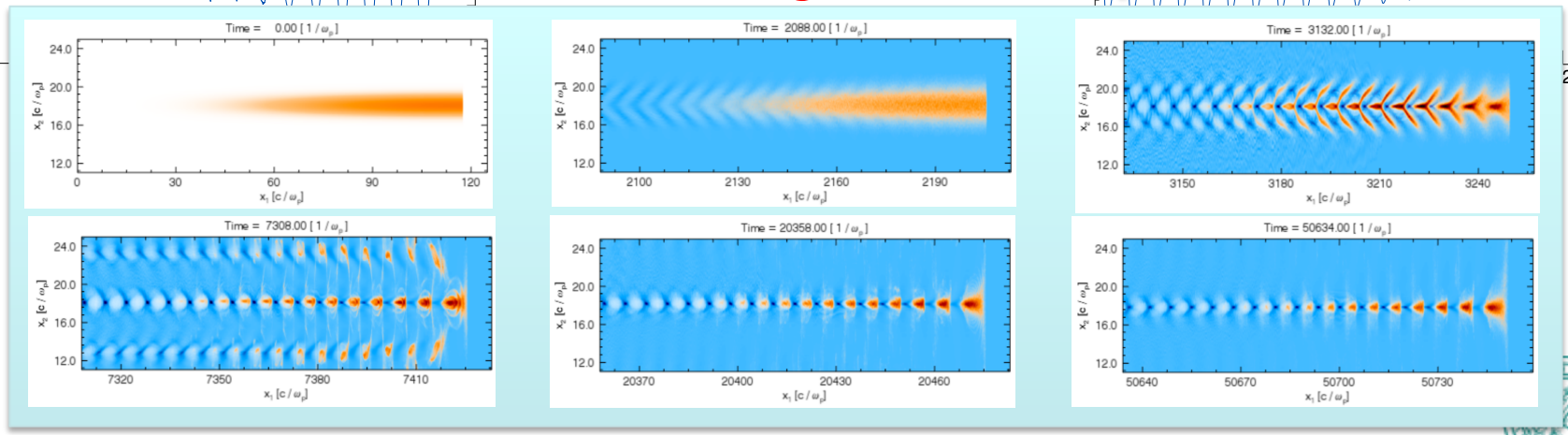




Radial!

NOT longitudinal!





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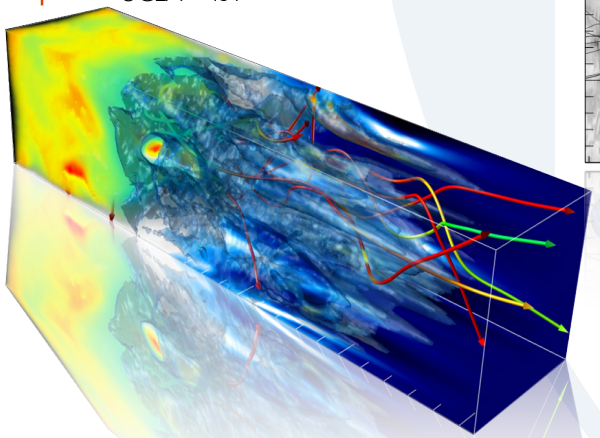
SMI-PWFA SiMULATiONS

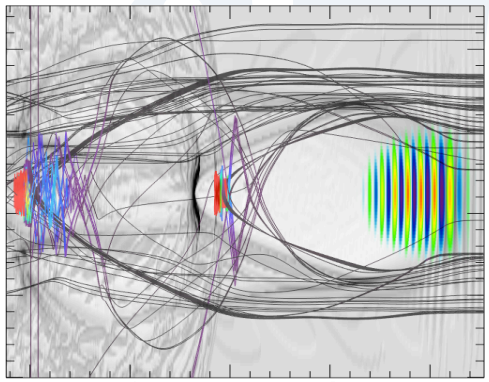
OSIRIS 2.0

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





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/

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

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

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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(Werner-Heisenberg-Institut)

OUTLINE

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ENERGY SELF-MODULATION

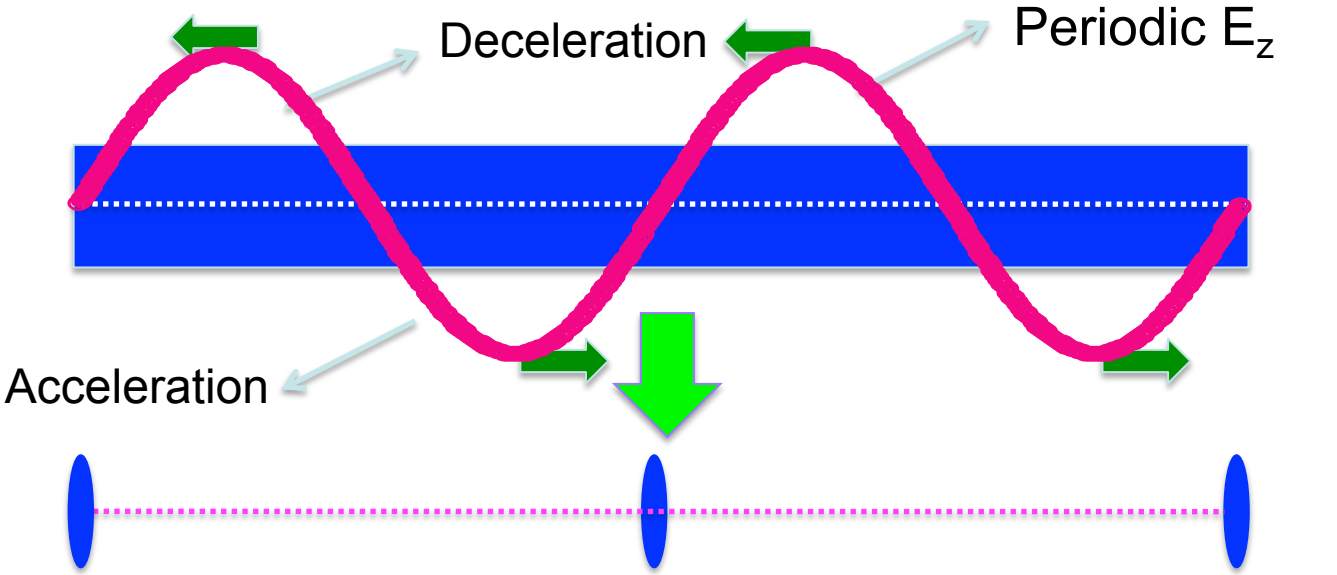
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

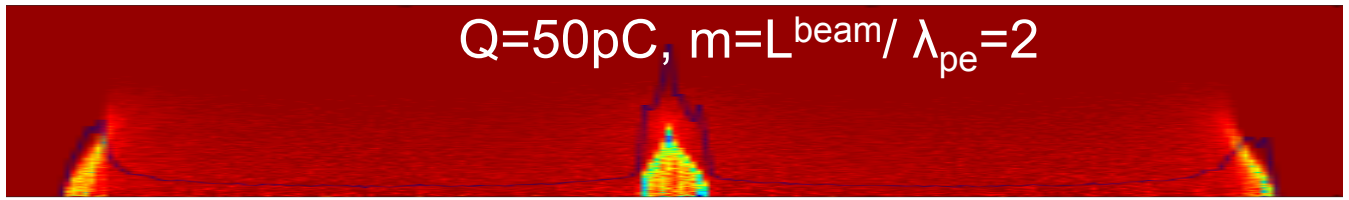
USC

BROOKHAVEN NATIONAL LABORATORY

Low — Energy ΔE_0 → High

Front — Back





- Similar to FEL energy modulation / velocity bunching
- Indirect evidence ($W_{//}=E_z$) of driving of wakefields that can seed the SMI: $W_{perp}=(E_r-cB_\theta)\alpha W_{//}$

Energy Gain/Loss:

$$\Delta E = \frac{1}{4}\cdot\frac{\Delta E_0}{m} \qquad m = L^{beam}/\lambda_{pe} = 1,2,..$$

$$E_z = \frac{1}{4}\cdot\frac{\Delta E_0}{m\cdot eL^{plasma}}$$

E_z must decreases from ~6 to ~1.2MV/m to preserve visibility! Choose Q=50pC

$$E_z(r=0) = \frac{-mQ}{\varepsilon_0 L_b^2 \sigma_r^2}\int_0^\infty e^{-r^2/2\sigma_r^2} K_0(2\pi m/L_b)\, r dr$$

m	$E_{z,\ opt}$ (MV/m)	$E_{z,\ lin,\ OSIRIS}$ (MV/m)	n_e~m^2 (cm^{-3})
1	5.2	3.7	1.2×10^{15}
2	3.0	3.2	4.8×10^{15}
3	2.0	2.6	1.1×10^{16}
4	1.5	2.1	1.9×10^{16}
5	1.2	1.8	3.0×10^{16}

Work by Y. Fang, USC

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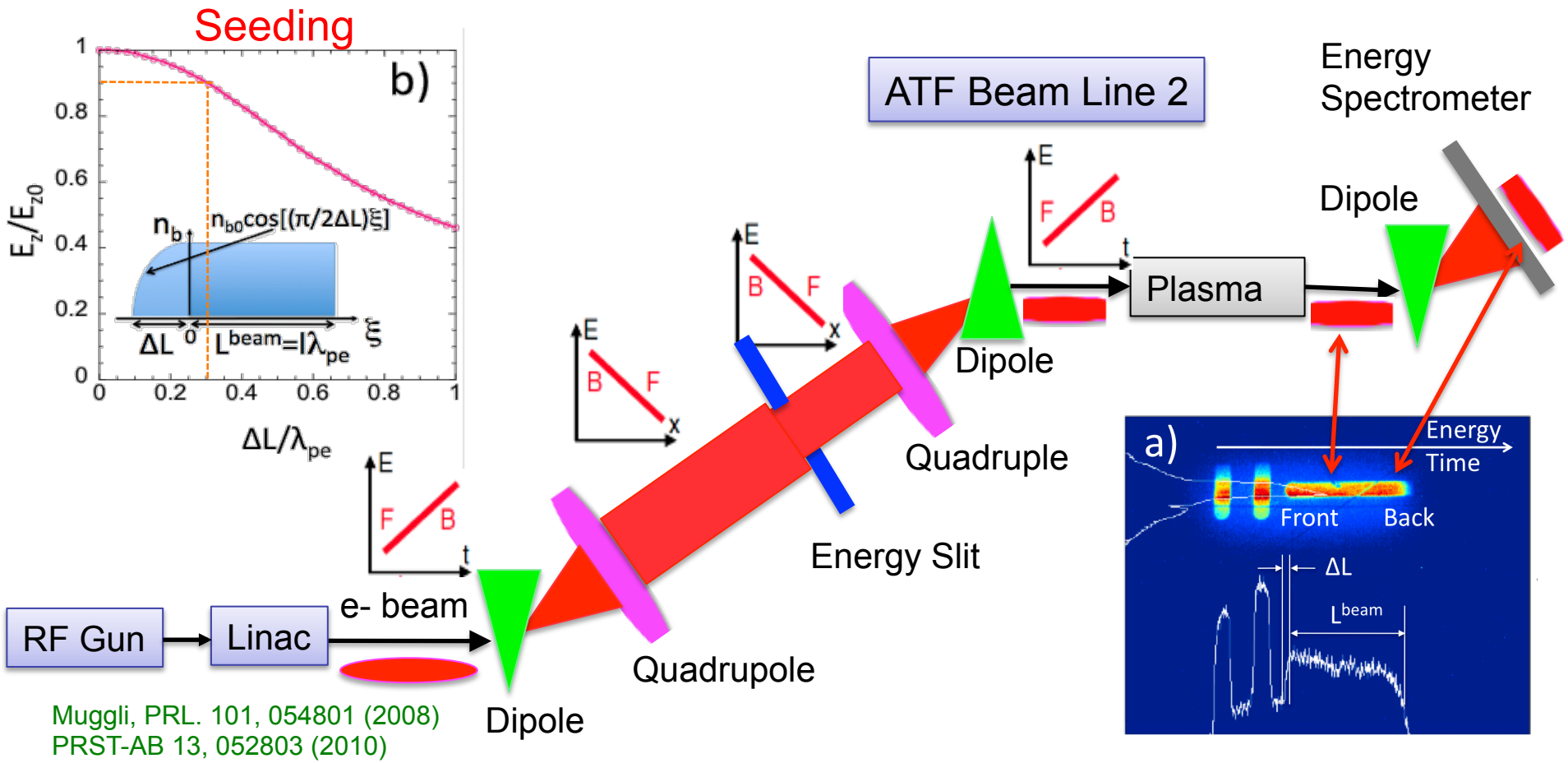
EXPERIMENTAL SETUP



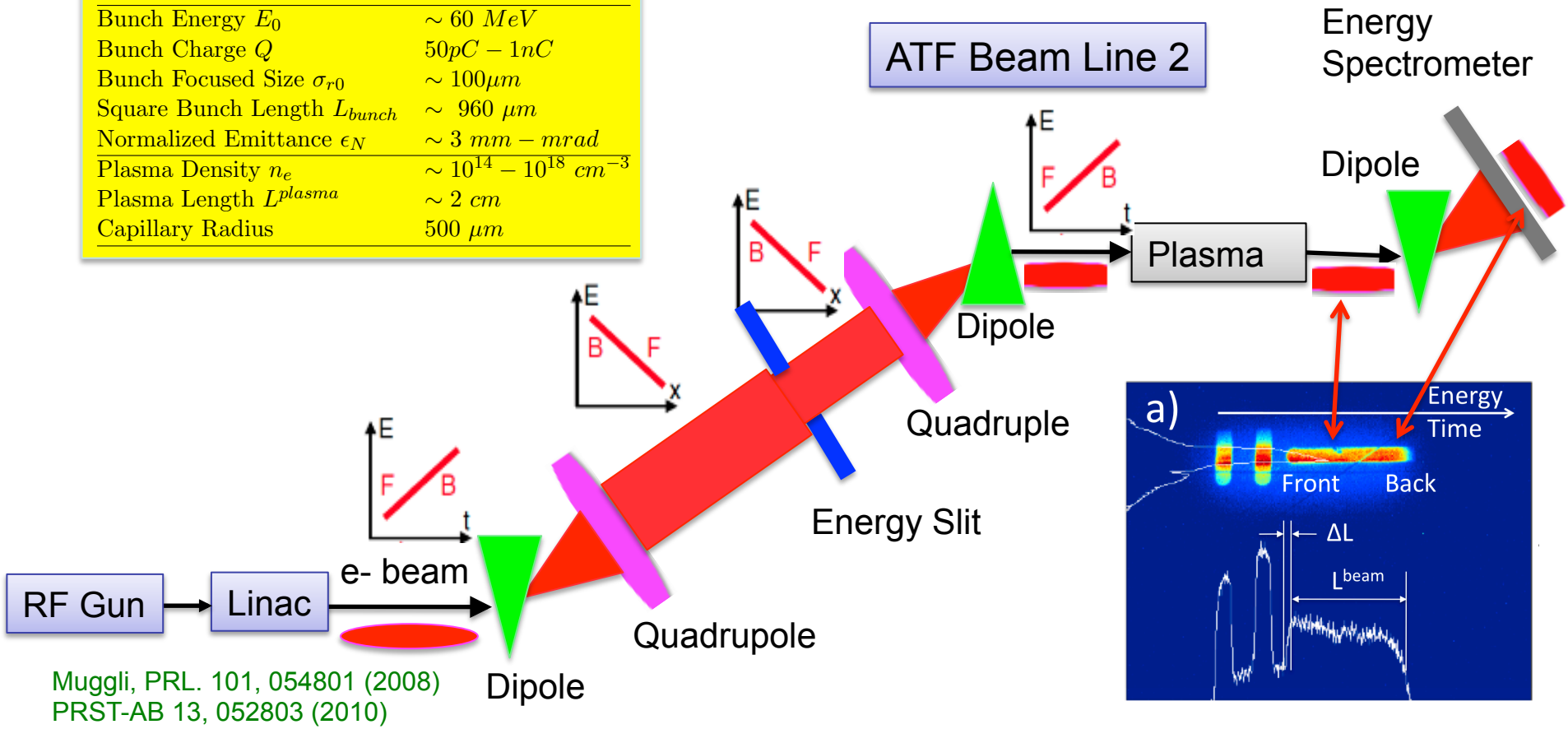
Muggli, PRL. 101, 054801 (2008)
PRST-AB 13, 052803 (2010)

- Use masking method to produce "square" bunch for SMI seeding
- Need cut/step<<λ_{pe}: <0.3λ_{pe} in exp. => E_{z0}>0.9$E_{z0\ sharp}$

Work by Y. Fang, USC

EXPERIMENTAL SETUP

Parameter	Value
Bunch Energy E_0	$\sim 60\ MeV$
Bunch Charge Q	$50pC - 1nC$
Bunch Focused Size σ_{r0}	$\sim 100\mu m$
Square Bunch Length L_{bunch}	$\sim\ 960\ \mu m$
Normalized Emittance ϵ_N	$\sim 3\ mm - mrad$
Plasma Density n_e	$\sim 10^{14} - 10^{18}\ cm^{-3}$
Plasma Length L^{plasma}	$\sim 2\ cm$
Capillary Radius	$500\ \mu m$



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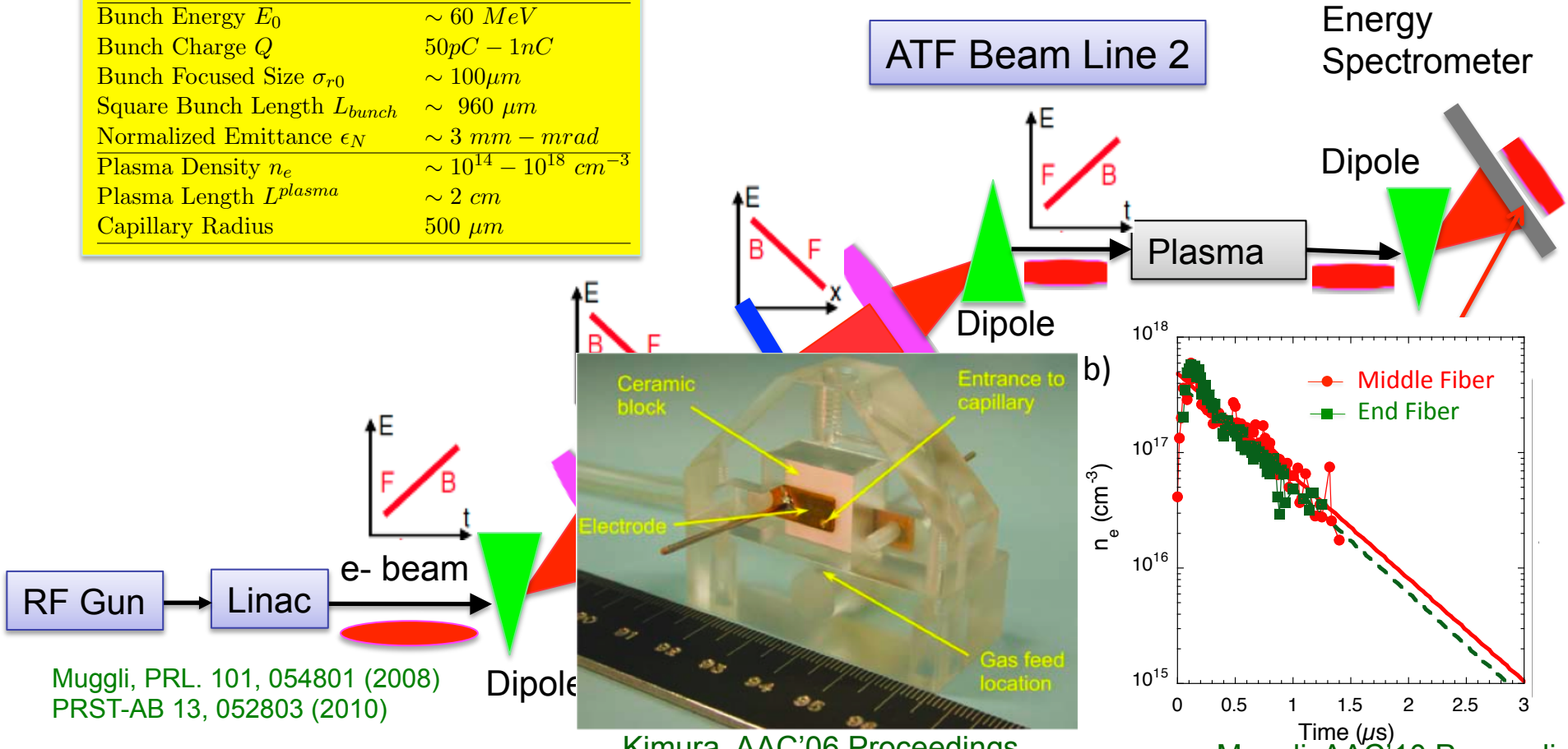

Muggli, PRL. 101, 054801 (2008)
PRST-AB 13, 052803 (2010)

Kimura, AAC'06 Proceedings

Muggli, AAC'10 Proceedings

✧n_e ⇔ discharge – beam delay

Work by Y. Fang, USC

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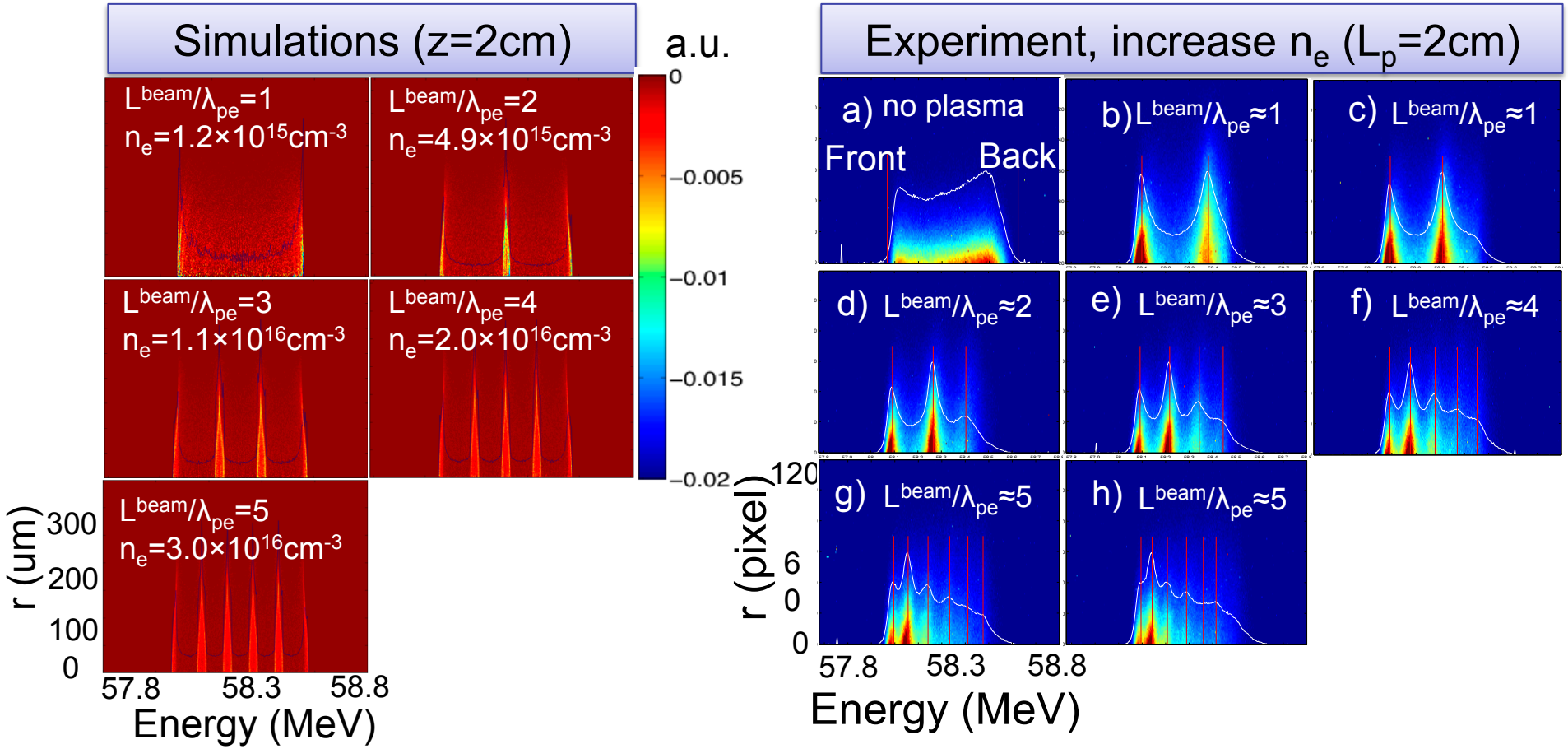
OBSERVATiON OF (ENERGY) SELF-MODULATiON

✧ATF "square" e⁻ bunch, Q=50pC, ΔE_0=0.5MeV in 960μm, in 2m plasma, variable n_e



Fang et al., PRL 112, 045001 (2014).

✧Simulations/experiments very similar

✧Visibility in experiment confirms E_z variation with n_e

✧First observation of SMI seed: E_z instead of E_r-cB_θ

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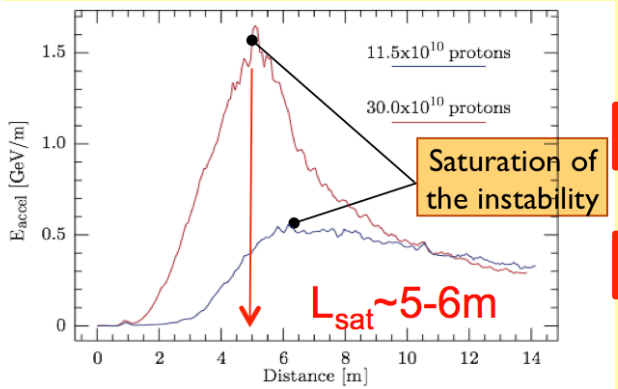
SM-PWFA PARAMETERS

✧Experimental parameters determined by beam parameters

✧CERN AWAKE

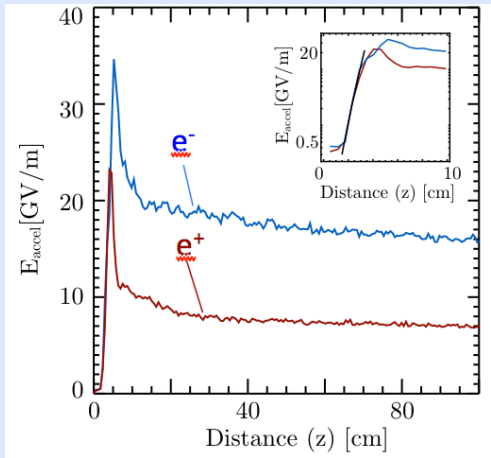
- p^+-driven
- SMI saturates in ~5m
- Study SMI or p^+-bunches
- Remain in ~linear PWFA regime
- ~GV/m over 10^+ m
- Externally inject e^-
- Accelerator experiments

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



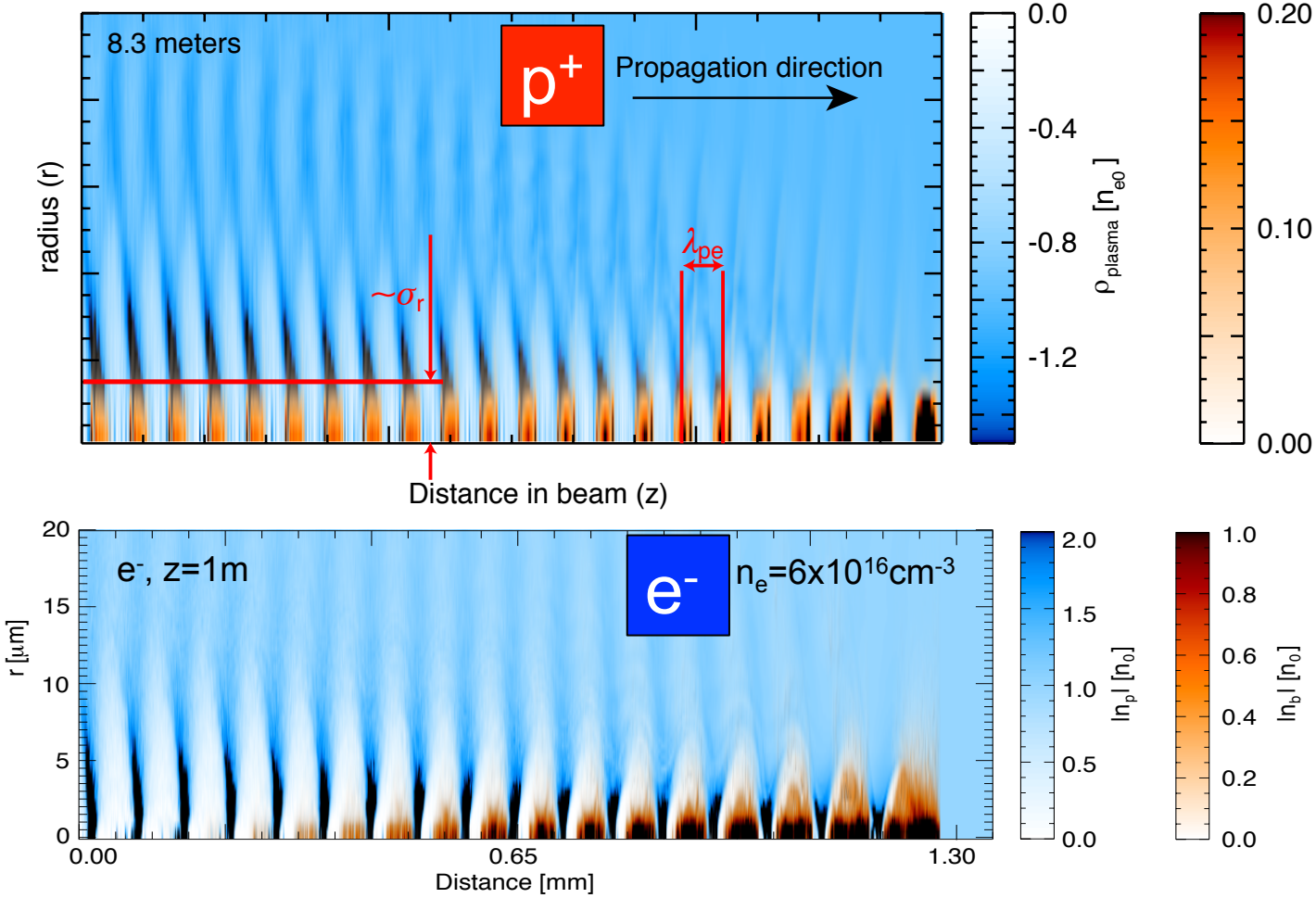
✧SLAC E209

- 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 physics



COMPARiSON +/- DRiVEN PWFA

✧Comparison positively/negatively charged bunches



AWAKE p+

SLAC e+

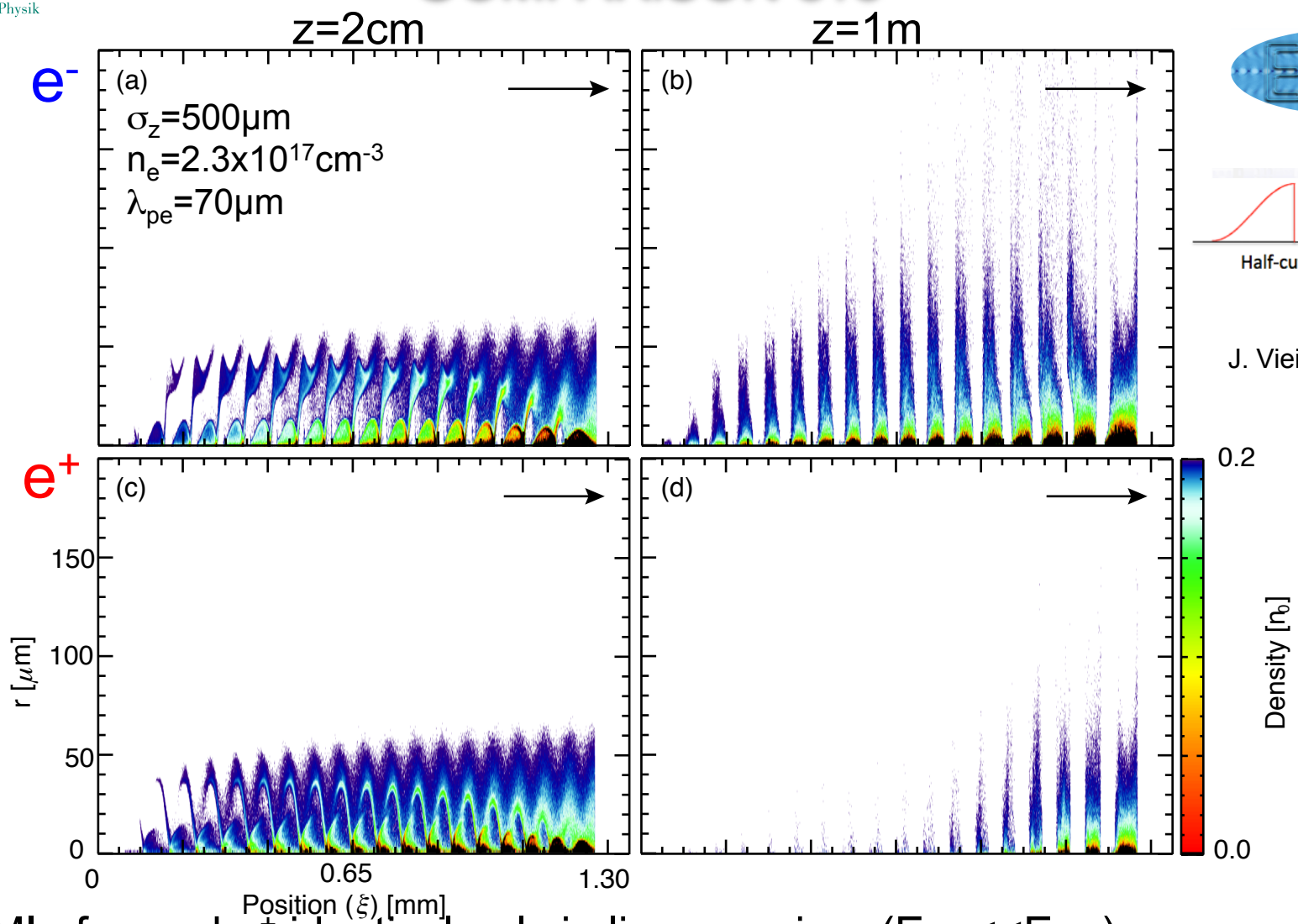
SLAC e-

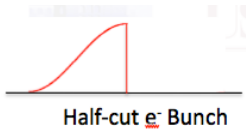
Simulations: J. Vieira

✧Phase difference, as expected from simple physics

Vieira, Phys. Plasmas 19, 063105 (2012)

COMPARiSON e⁻/e⁺





J. Vieira, IST

- ✧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

Vieira, Phys. Plasmas 19, 063105 (2012)

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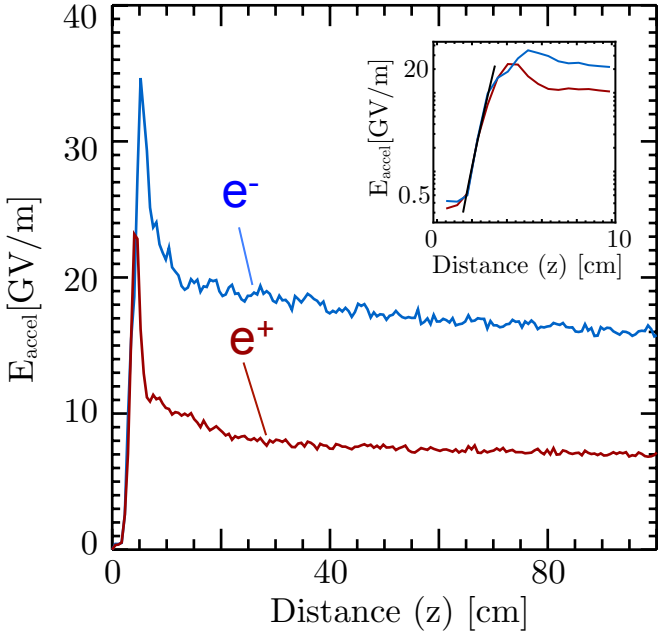
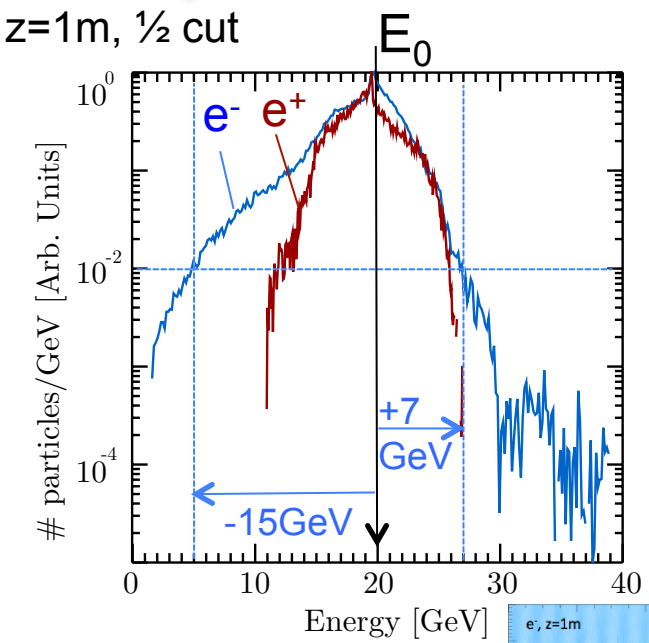
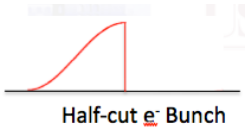
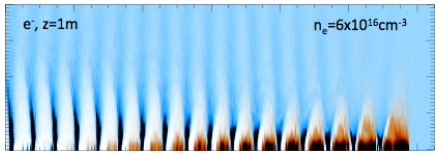
WAKEFIELDS & ENERGY CHANGE
(by drive particles)









- 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

Vieira, Phys. Plasmas 19, 063105 (2012)

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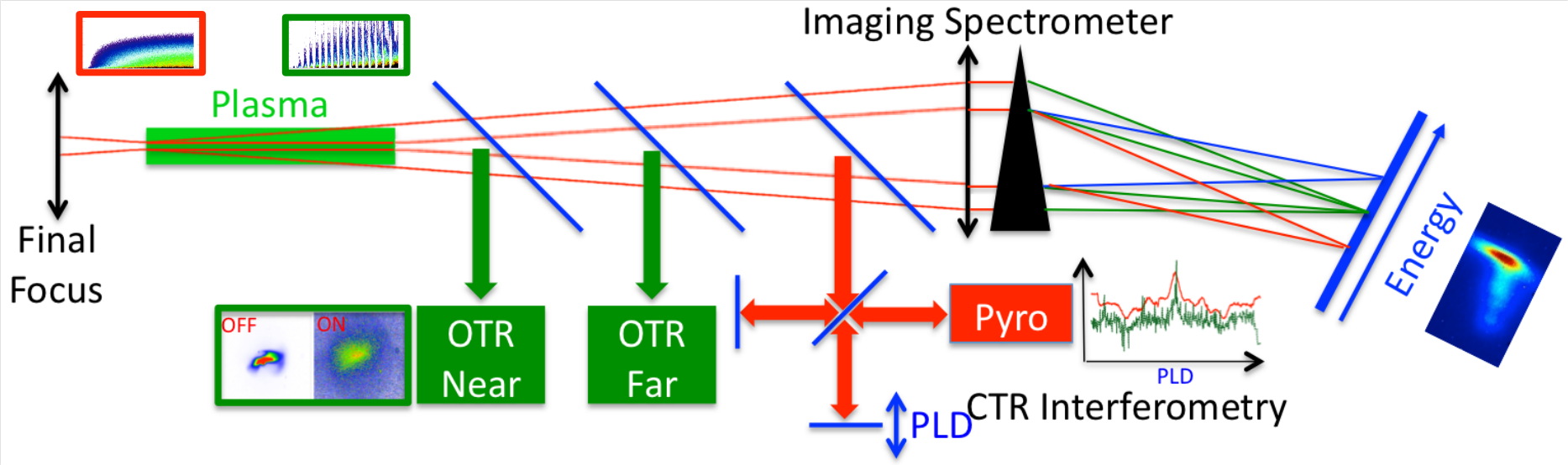
E209 @ SLAC

The same as E200 and E201



Three observables:

- ✧Energy loss/gain by drive bunch particles
- ✧Formation of transverse halo (defocused particles)
- ✧Radial size modulation (CTR interferometry)

Three well established diagnostics at FACET:

- ✧Magnetic spectrometer with ~100MeV resolution
- ✧Two OTR systems ~1 and ~2m downstream from the plasma
- ✧CTR interferometry ~1.5m downstream from the plasma

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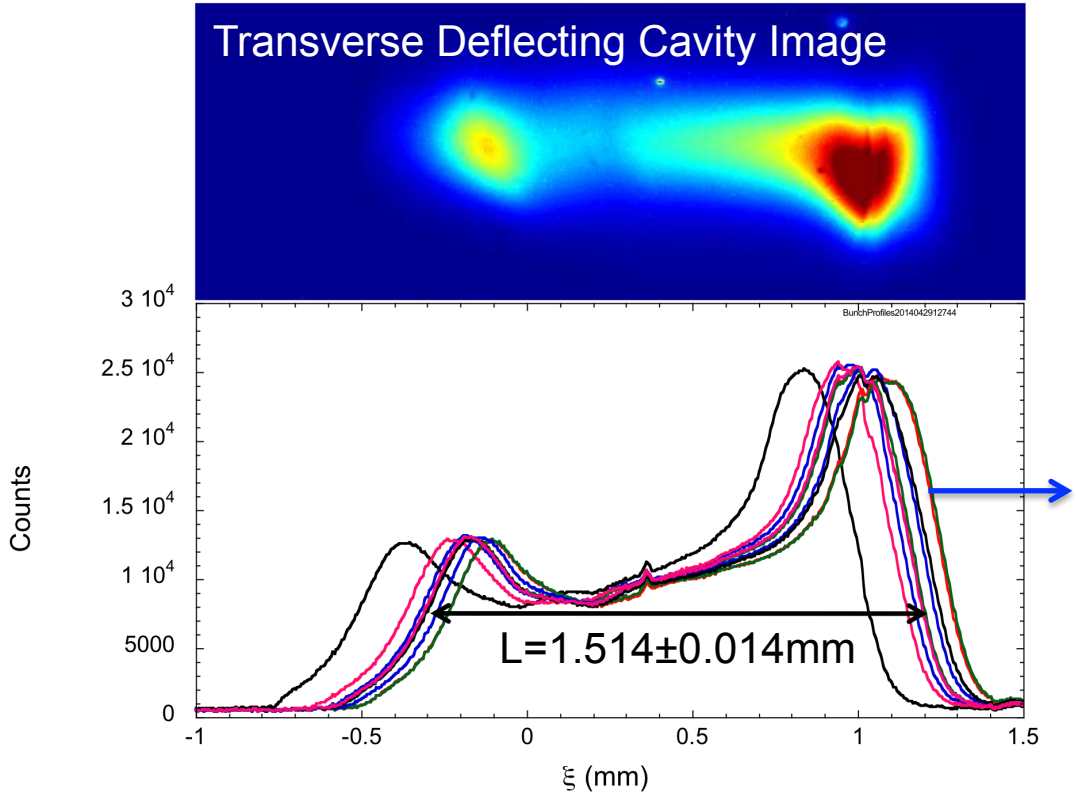
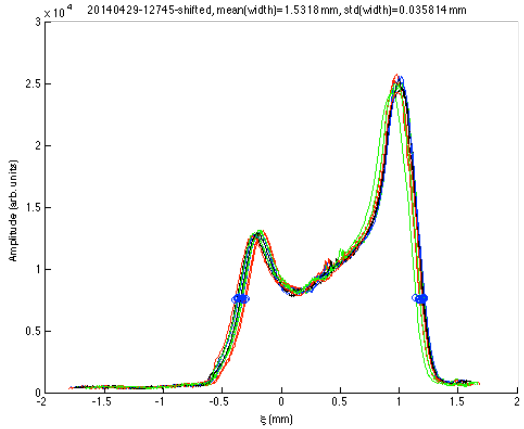
BEAM & PLASMA PARAMETERS



Two sets of ten, aligned profiles ….



✧Bunch longitudinal profile very consistent …

✧$L_{blue\ points}$=1.514±0.014mm

<u>e^- beam:</u>

E=20.35GeV

N_{e-}=1.9x10^{10}

σ_r~40μm

ξ~1500μm FWHM

L/λ_{pe}~14

n_b/n_e~2%

<u>Plasma (E200):</u>

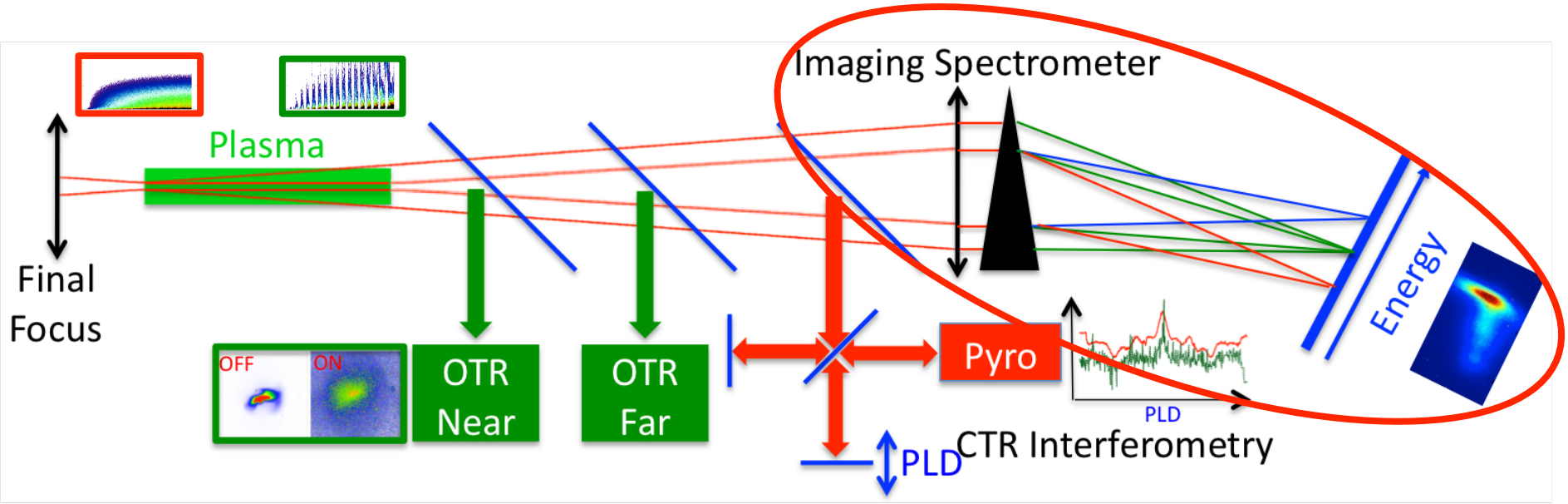
n_e=8x10^{16}cm^{-3} => λ_{pe}=115μm

L_p~1.3m

✧Discovery: the beam profile is far from Gaussian (i.e., not as in simulations, so far)

© P. Muggli

E209 @ SLAC



Three observables:

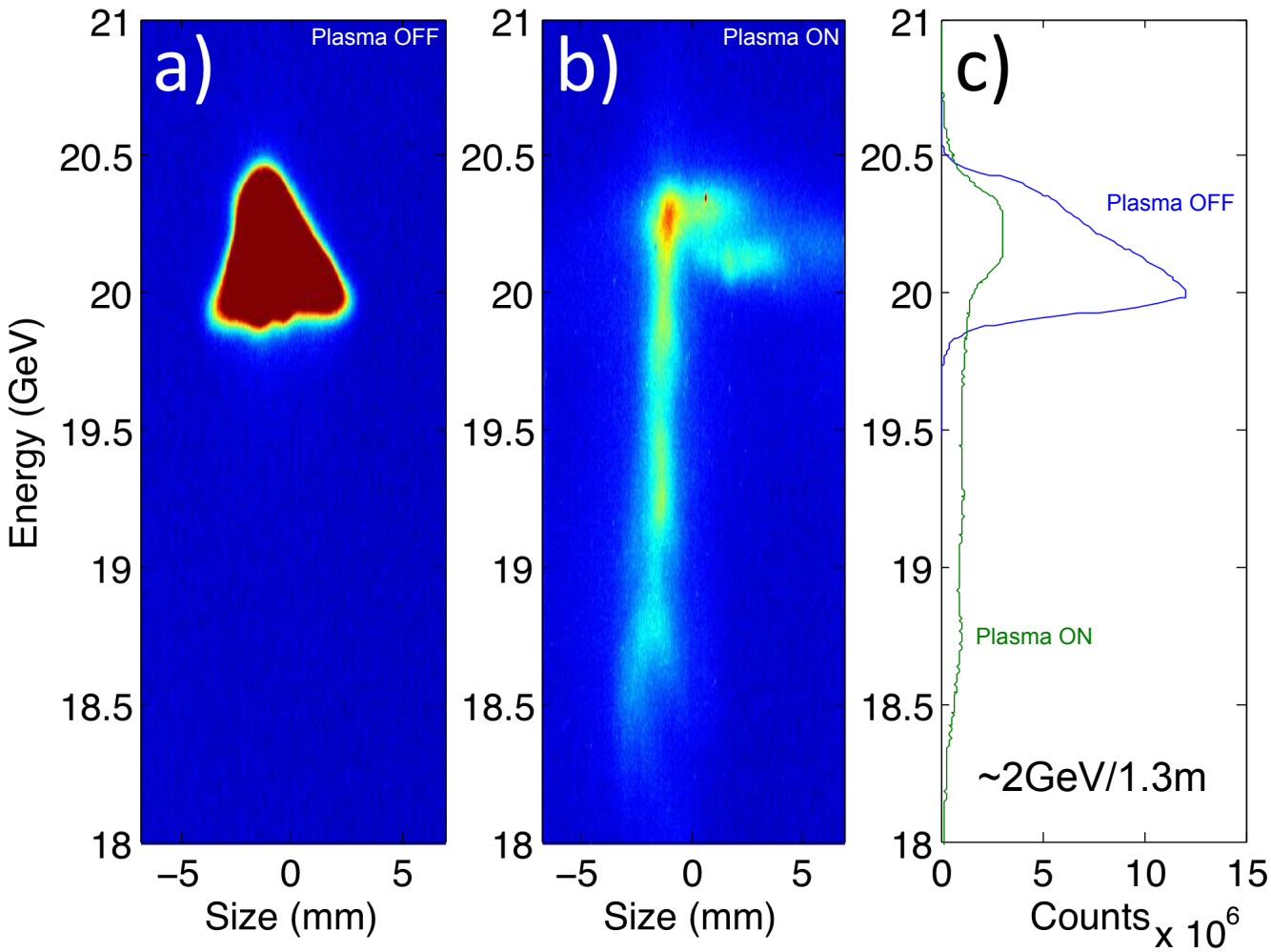
- ✧Energy loss/gain by drive bunch particles
- ✧Formation of transverse halo (defocused particles)
- ✧Radial size modulation (CTR interferometry)

Three well established diagnostics:

- ✧Magnetic spectrometer with ~100MeV resolution
- ✧Two OTR systems ~1 and ~2m downstream from the plasma
- ✧CTR interferometry ~1.5m downstream from the plasma

© P. Muggli

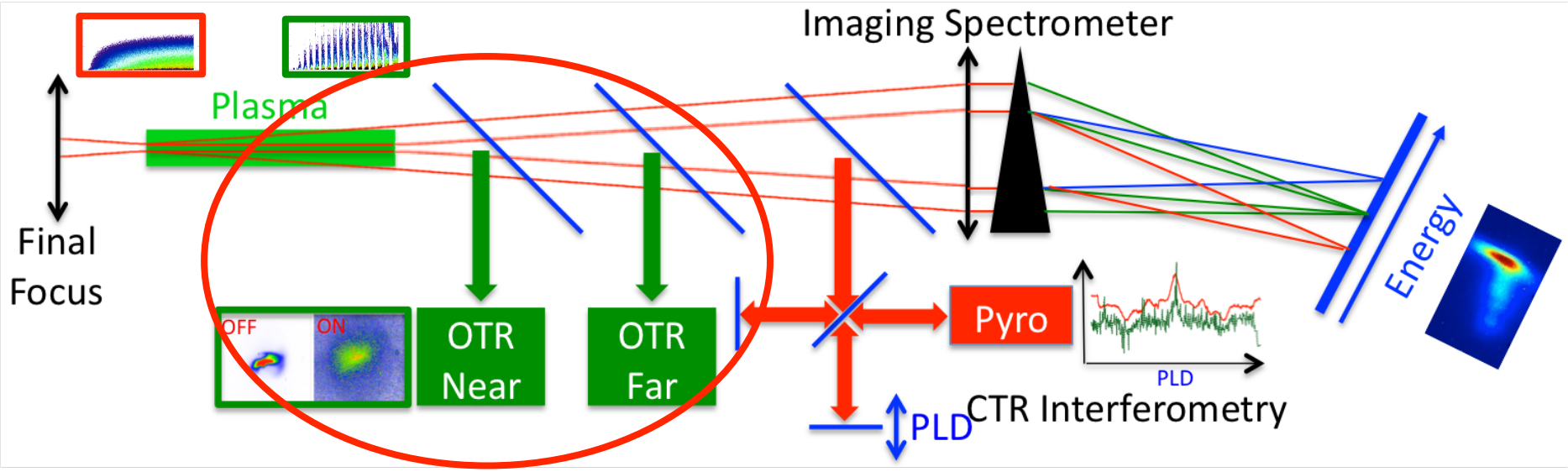
ENERGY CHANGE



- >GeV/m wakefields driven by long (L/λ_{pe}~14) bunch in plasma
- Spatial structure in the energy spectrum ⇔ radial modulation?

© P. Muggli

E209 @ SLAC



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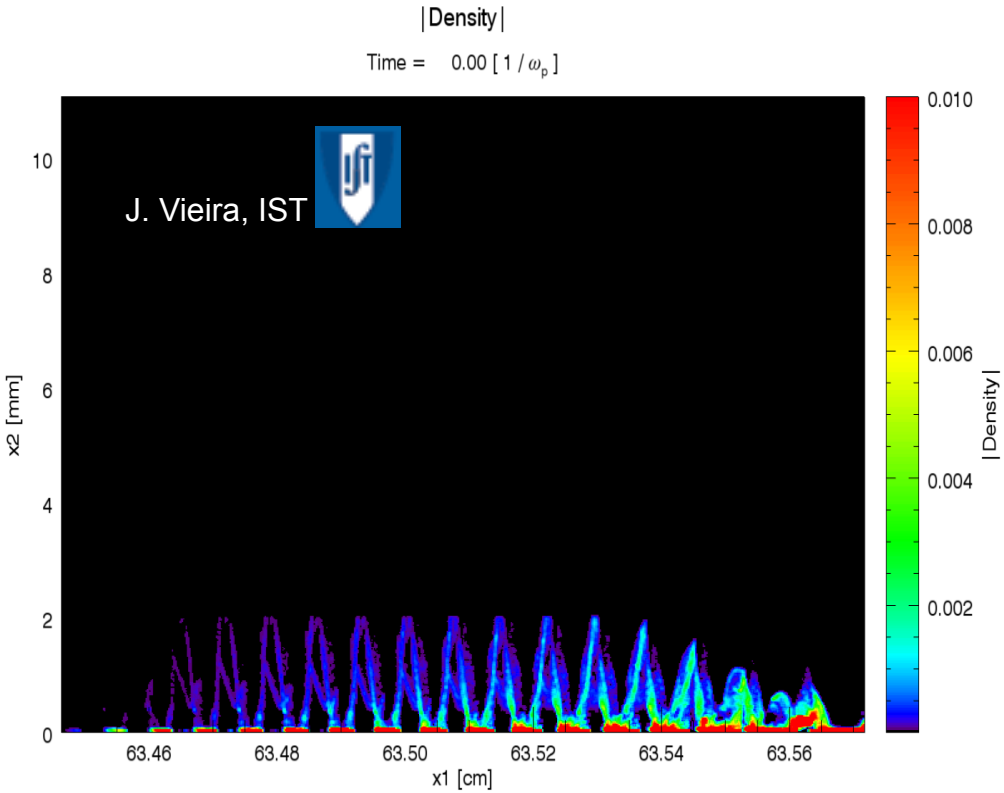
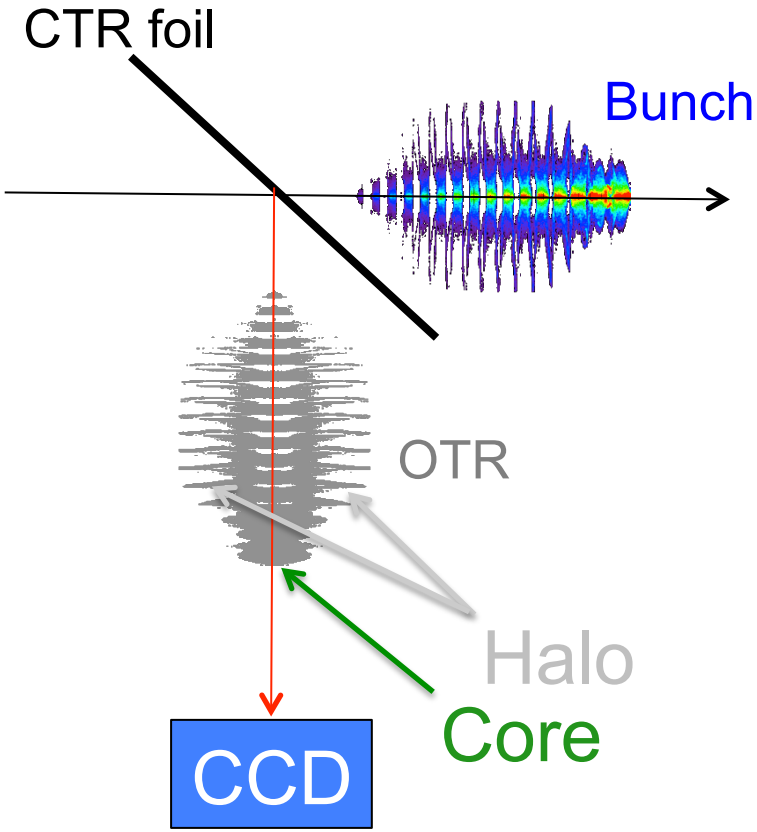
PROPAGATION AFTER THE PLASMA



Beam propagation in vacuum-after plasma



✧ Measure time integrated transverse beam image: core + halo

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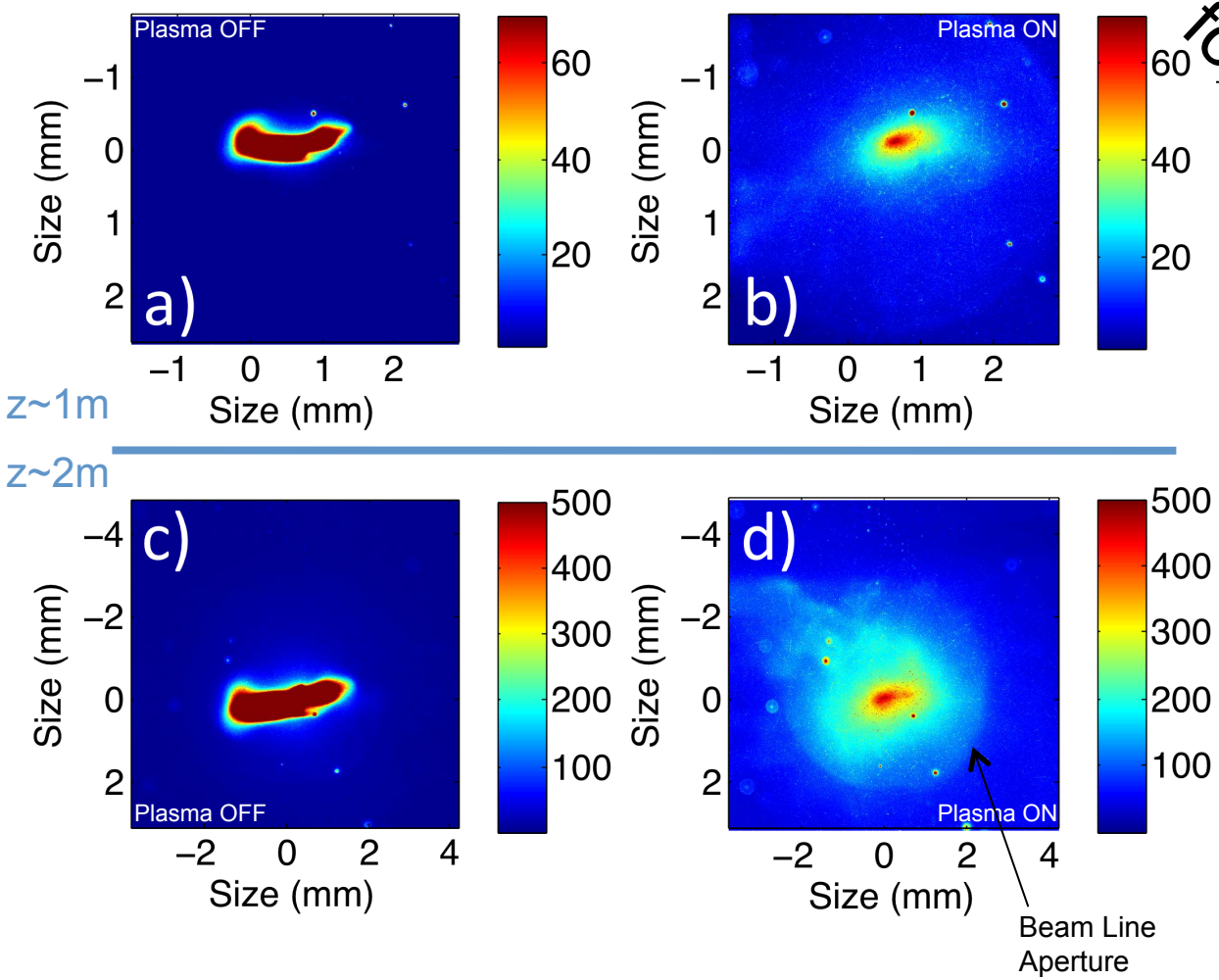
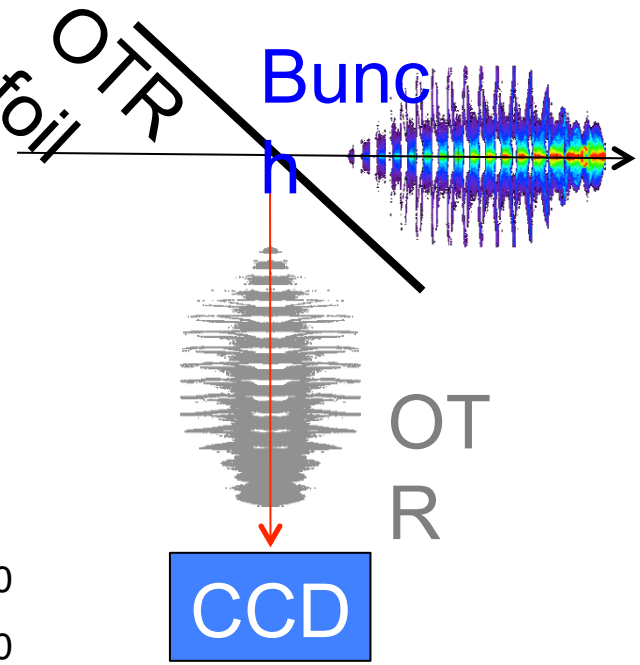
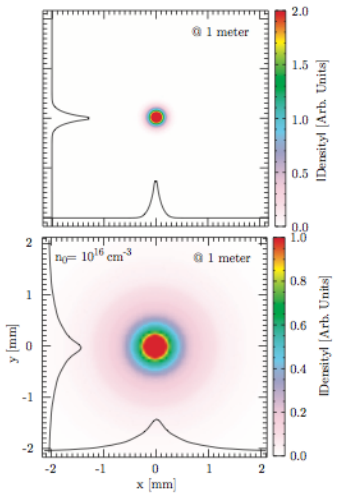
TRANSVERSE SIZE

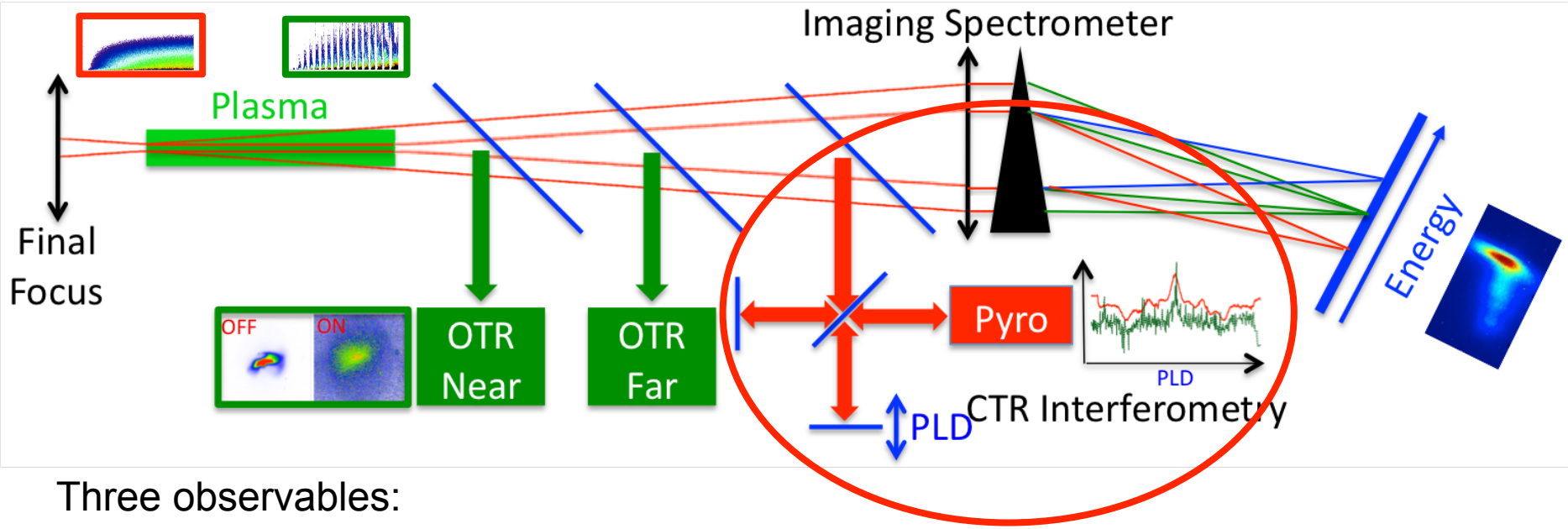






✧Core of "focused" and halo of "defocused" e-

E209 @ SLAC



Three observables:

- ✧Energy loss/gain by drive bunch particles
- ✧Formation of transverse halo (defocused particles)
- ✧Radial size modulation (CTR interferometry, CTRI)

Three well established diagnostics:

- ✧Magnetic spectrometer with ~100MeV resolution
- ✧Two OTR systems ~1 and ~2m downstream from the plasma
- ✧CTR interferometry ~1.5m downstream from the plasma (E201)

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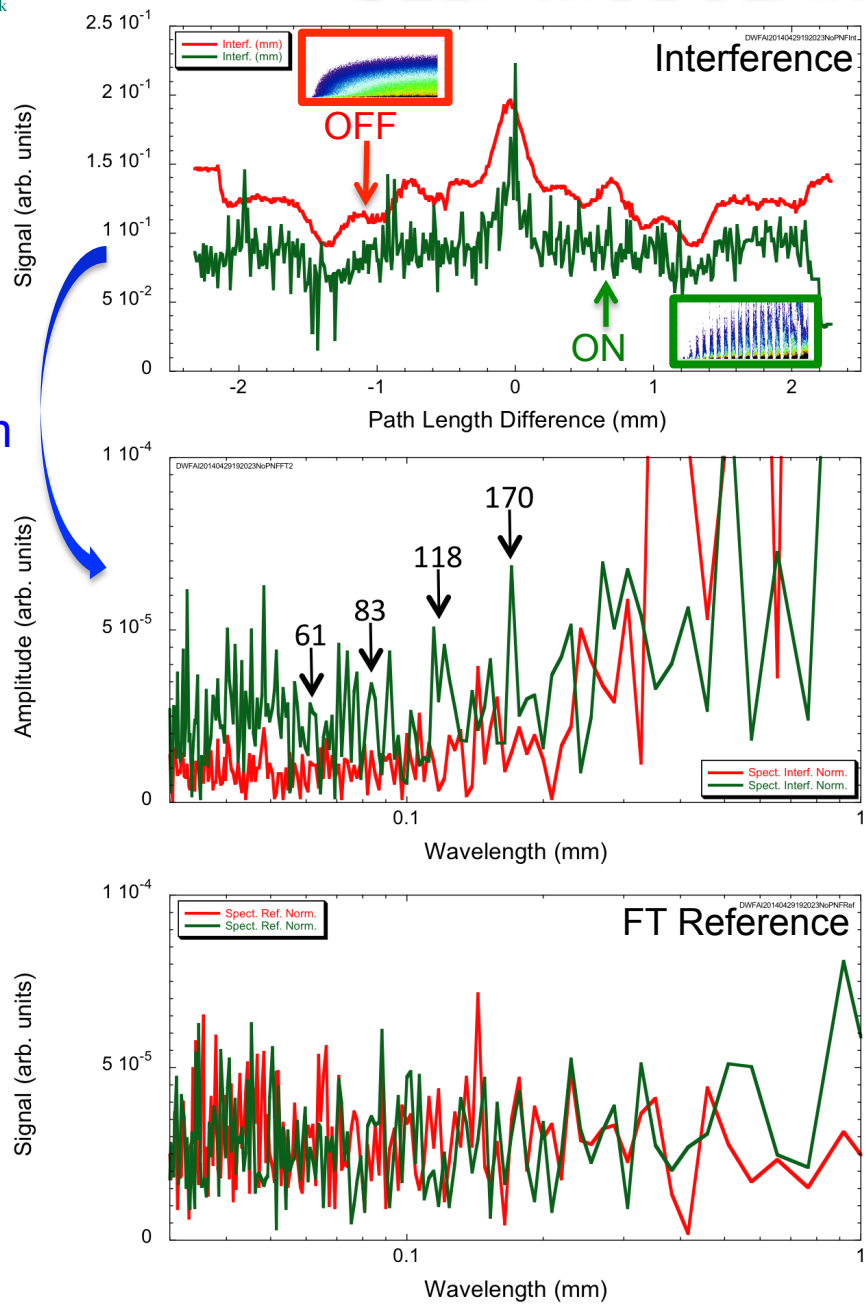
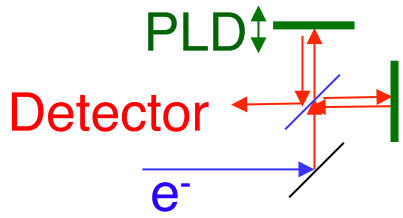
SELF-MODULATION SIGN

Fourier Transform





$$W(\Delta z) \propto \int_{-\infty}^{\infty} \left[\frac{1}{2} E_{CTR}(\xi) + \frac{1}{2} E_{CTR}(\xi + \Delta z) \right]^2 d\xi$$

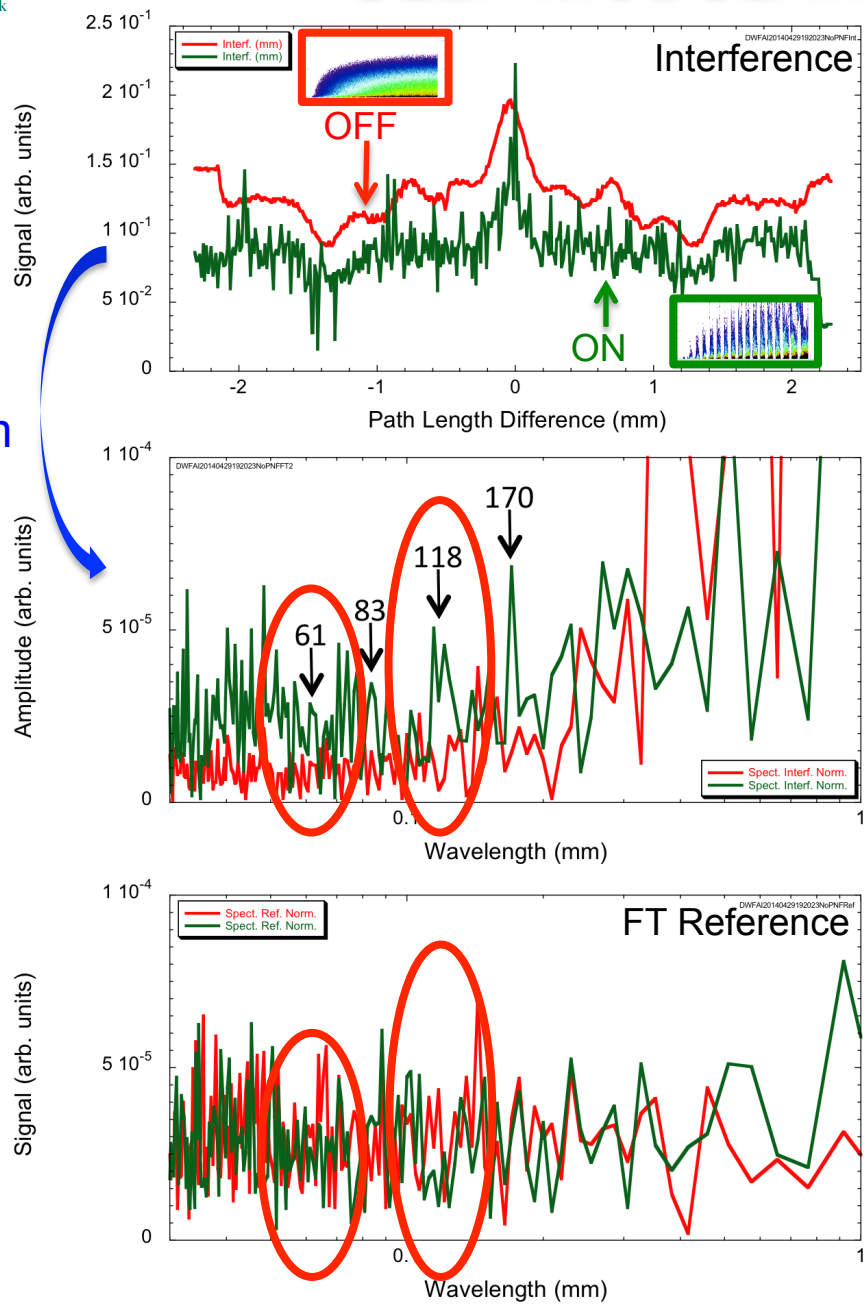
$n_e = 8 \times 10^{16} cm^{-3} \Rightarrow \lambda_{pe} = 115 \mu m$

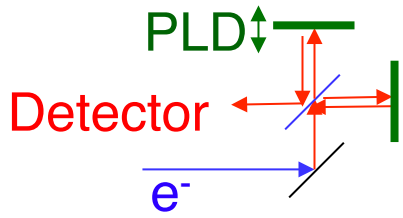
- ✧Short wavelength features
- ✧Peaks at ~λ_{pe} and ~$\lambda_{pe}/2$ in FT
- ✧Other peaks (170, 83µm)?
- ✧Peaks not in reference signal

© P. Muggli

SELF-MODULATION SIGN

Fourier Transform





$$W(\Delta z) \propto \int_{-\infty}^{\infty} \left[\frac{1}{2} E_{CTR}(\xi) + \frac{1}{2} E_{CTR}(\xi + \Delta z) \right]^2 d\xi$$

$n_e = 8 \times 10^{16} cm^{-3} \Rightarrow \lambda_{pe} = 0.115 mm$

- Short wavelength features
- Peaks at ~λ_{pe} and ~$\lambda_{pe}/2$ in FT
- Other peaks (170, 83μm)?
- Peaks not in reference signal

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

OUTLINE

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

MAX-PLANCK-GESELLSCHAFT

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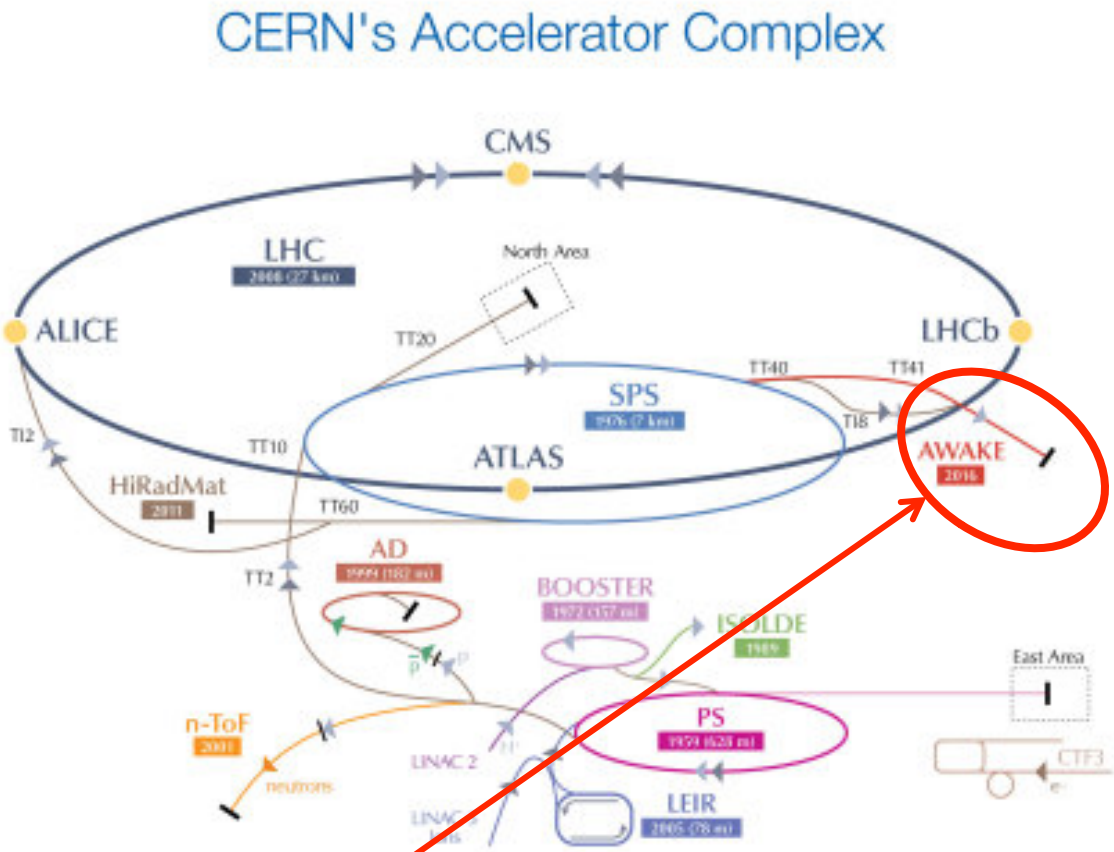
PROTON BEAMS @ CERN



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

$n_e \sim 7\times10^{14}\,cm^{-3}$ for $k_p\sigma_r \approx 1$
$\lambda_{pe} \sim 1.3mm << \sigma_z$
$f_{pe} \sim 240GHz$
$L_p \sim 10m \sim 2\beta^*$

AWAKE experimental area

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

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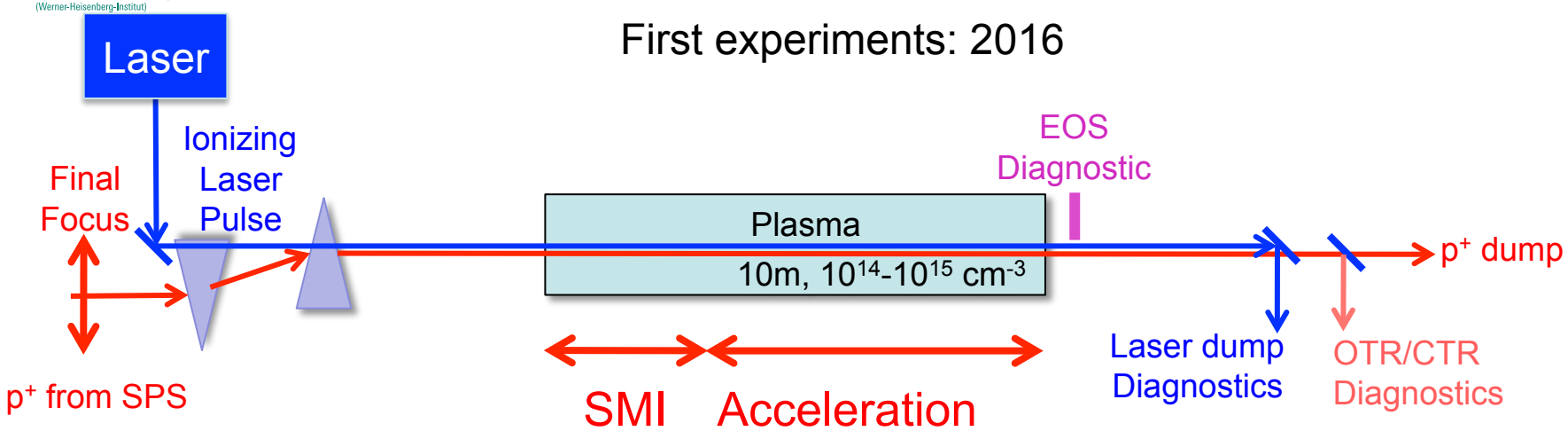
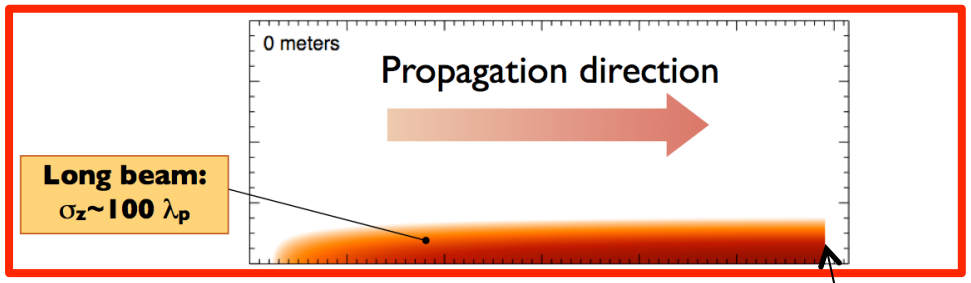
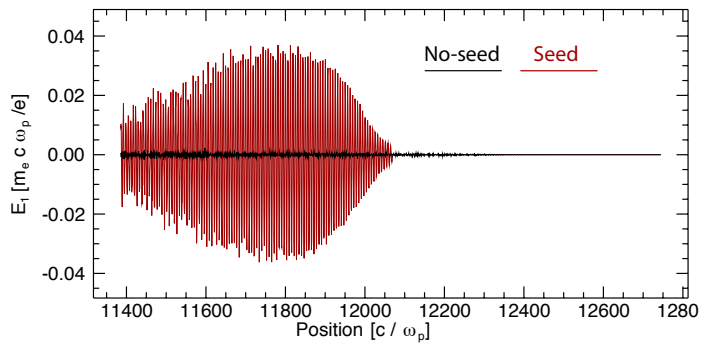
AWAKE EXPERIMENT @ CERN

First experiments: 2016







✧No seed no SMI (over 10m)

"Sharp" (<<λ_{pe}) start of the beam/plasma interaction for SMI seeding
AWAKE: will seed with ionization front!

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

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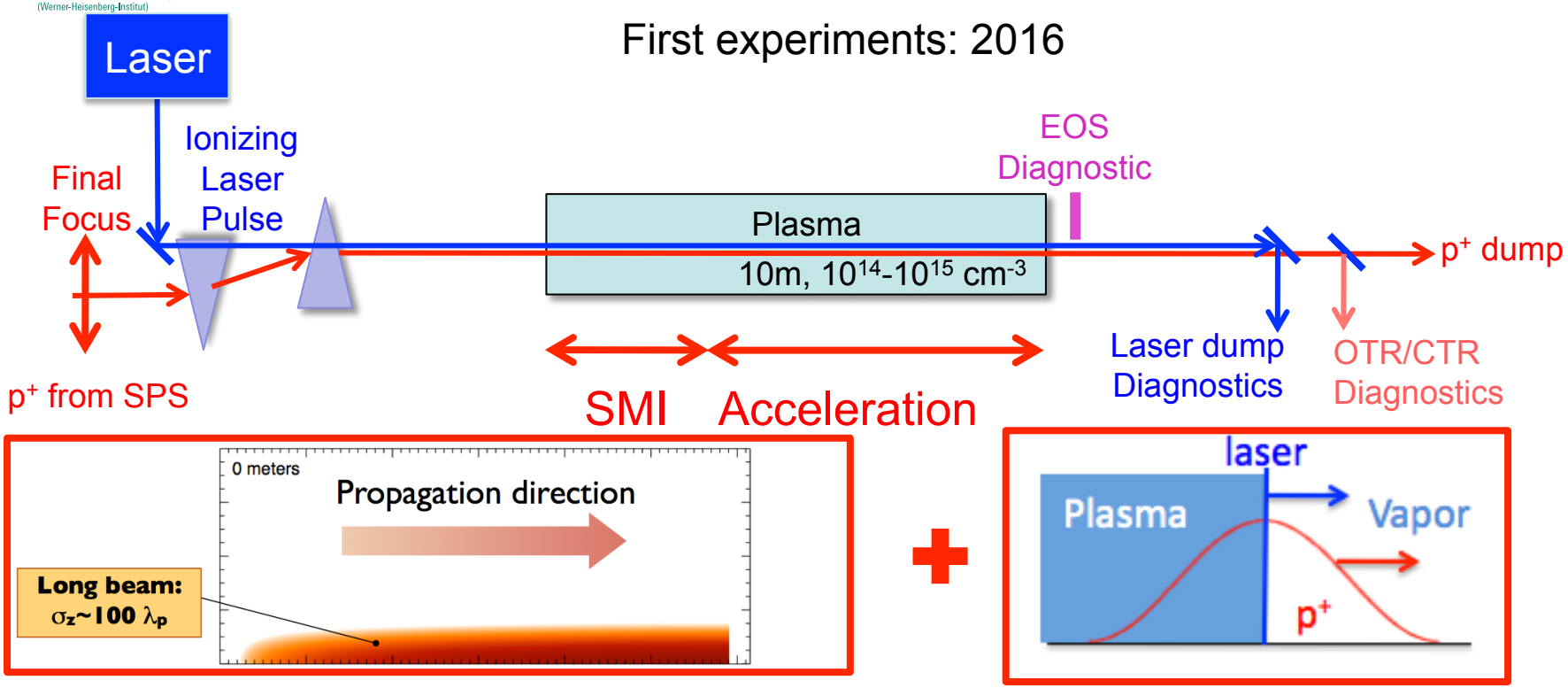
AWAKE EXPERIMENT @ CERN

First experiments: 2016



- Short laser pulse creates the plasma and seeds the SMI
- σ_z~12cm >> λ_{pe}~1.2mm (n_e~7x$10^{14}$$cm^{-3}$) => Self-modulation Instability (SMI)*
- $\sigma_{z\ laser}$~30μm<<λ_{pe} => good seed

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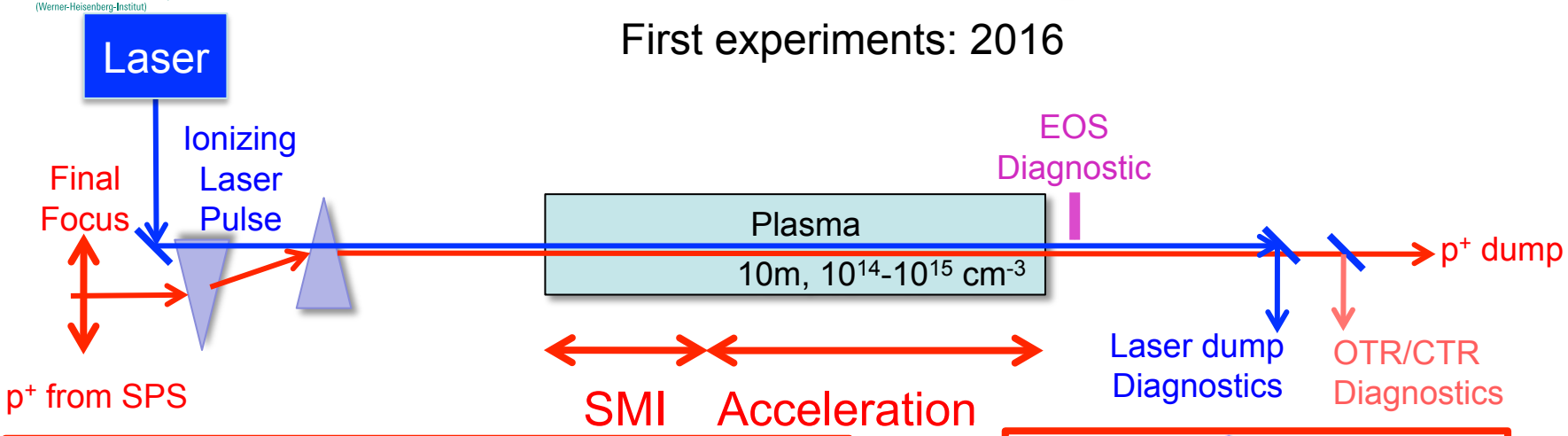
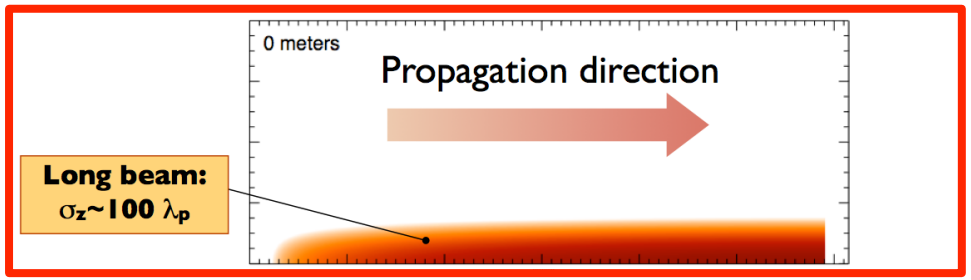
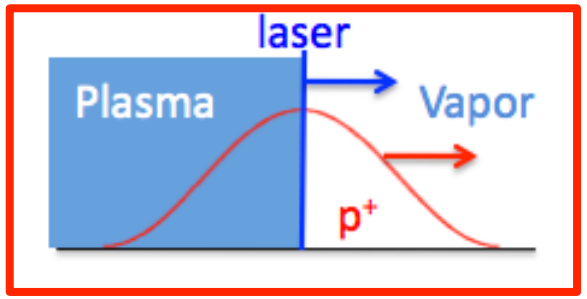
*Kumar, Phys. Rev. Lett. 104, 255003 (2010)

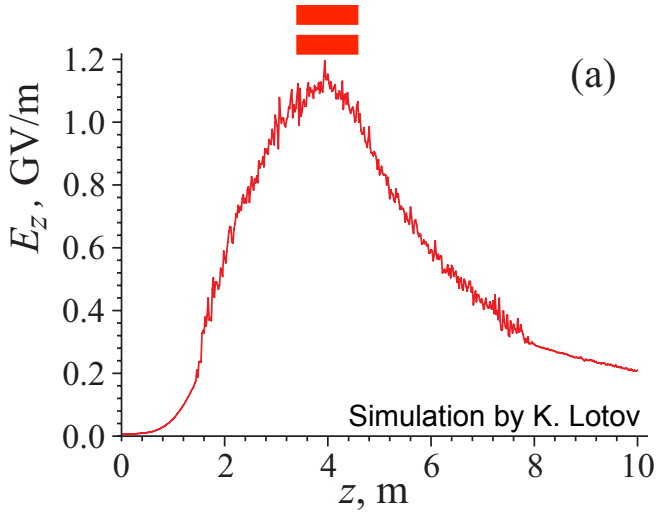
AWAKE EXPERIMENT @ CERN

First experiments: 2016









✧ The wakefields grow …

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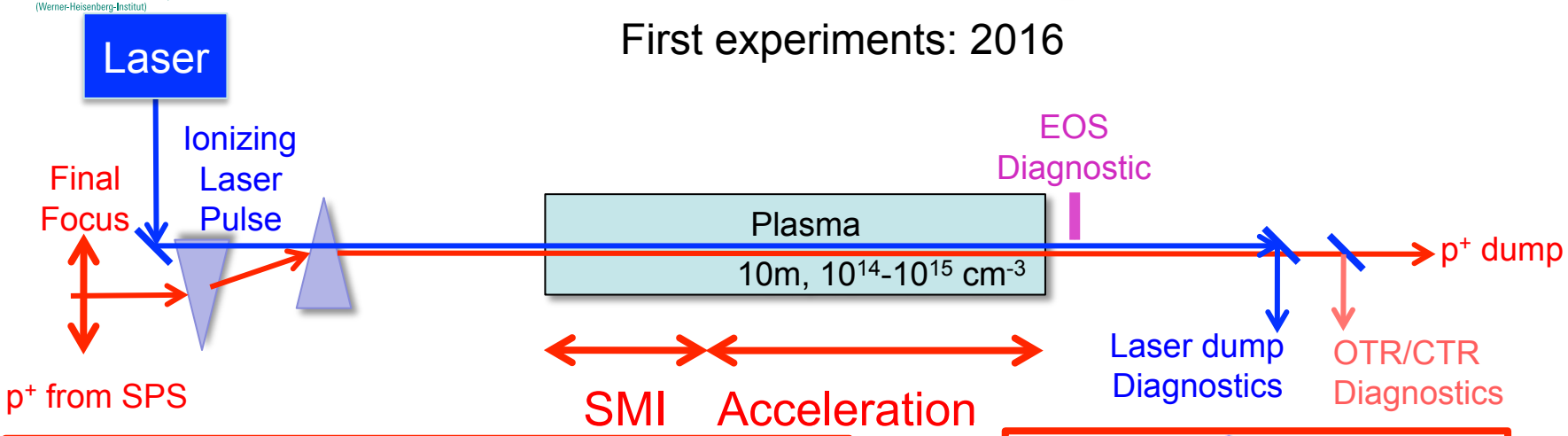
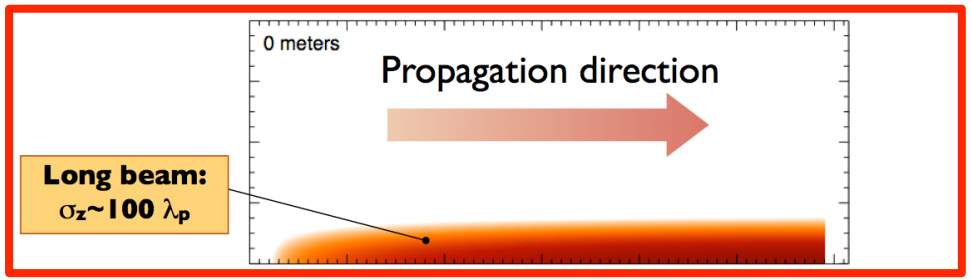
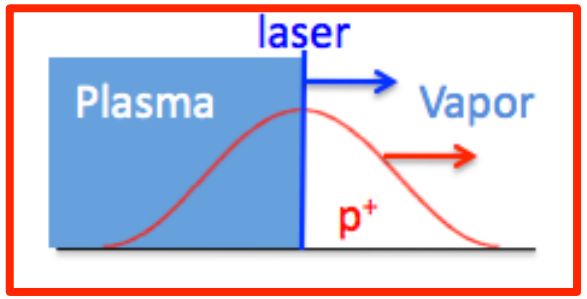
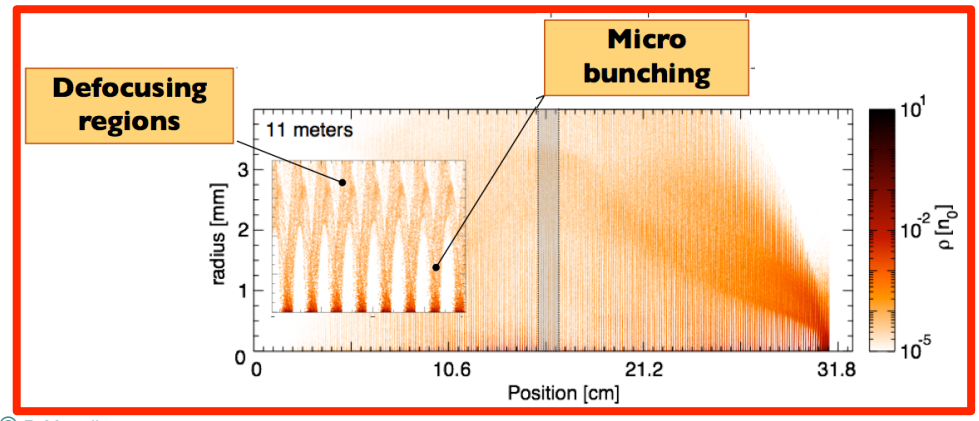
AWAKE EXPERIMENT @ CERN

First experiments: 2016





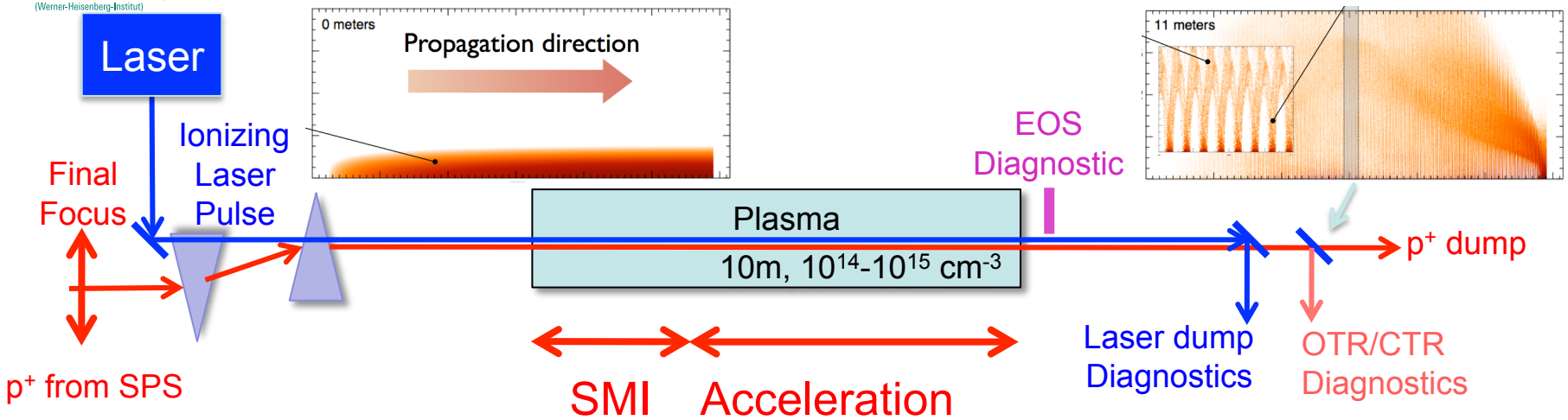


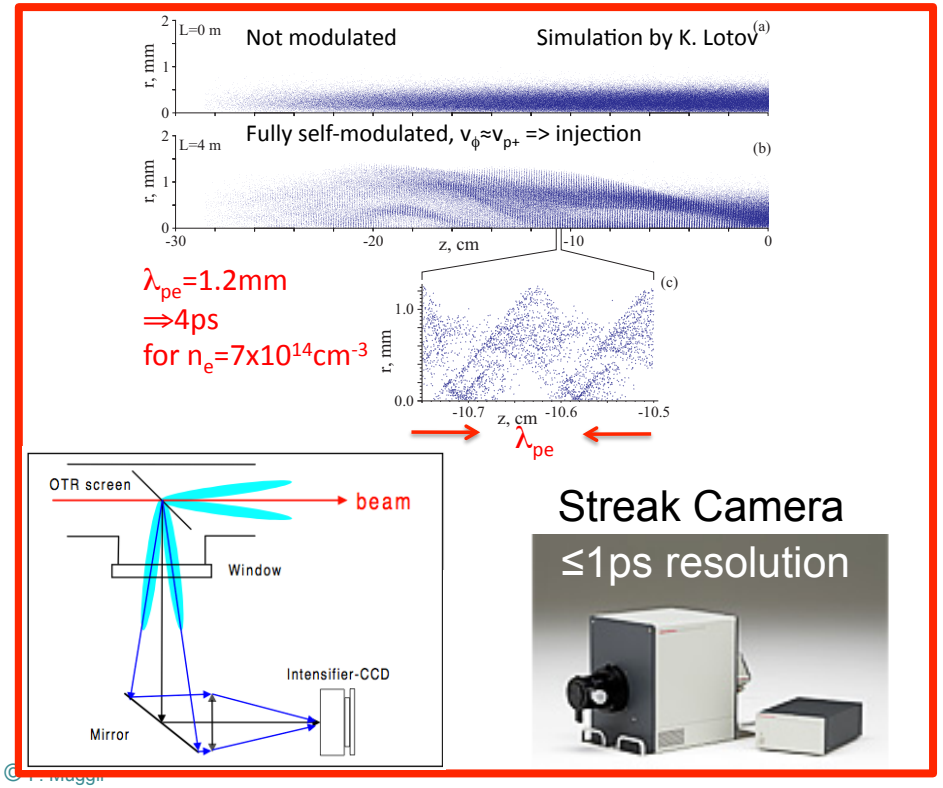


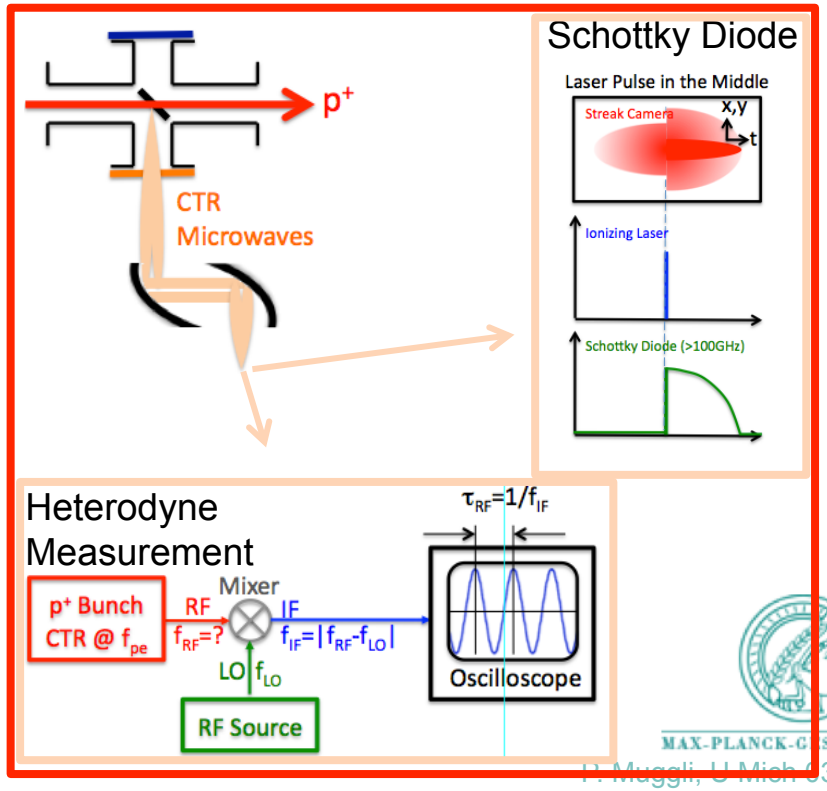
✧ The long (σ_z~12cm) p^+ bunch self-modulates with period λ_{pe}~1.2mm (n_e~7x10^{14}cm^{-3})

© P. Muggli

SMI DIAGNOSTICS







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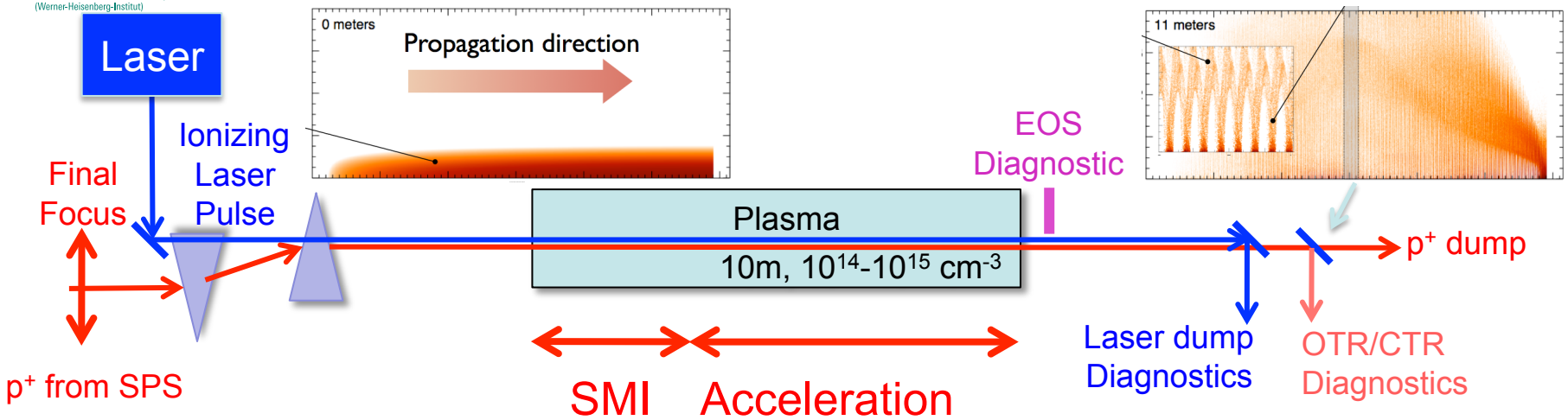
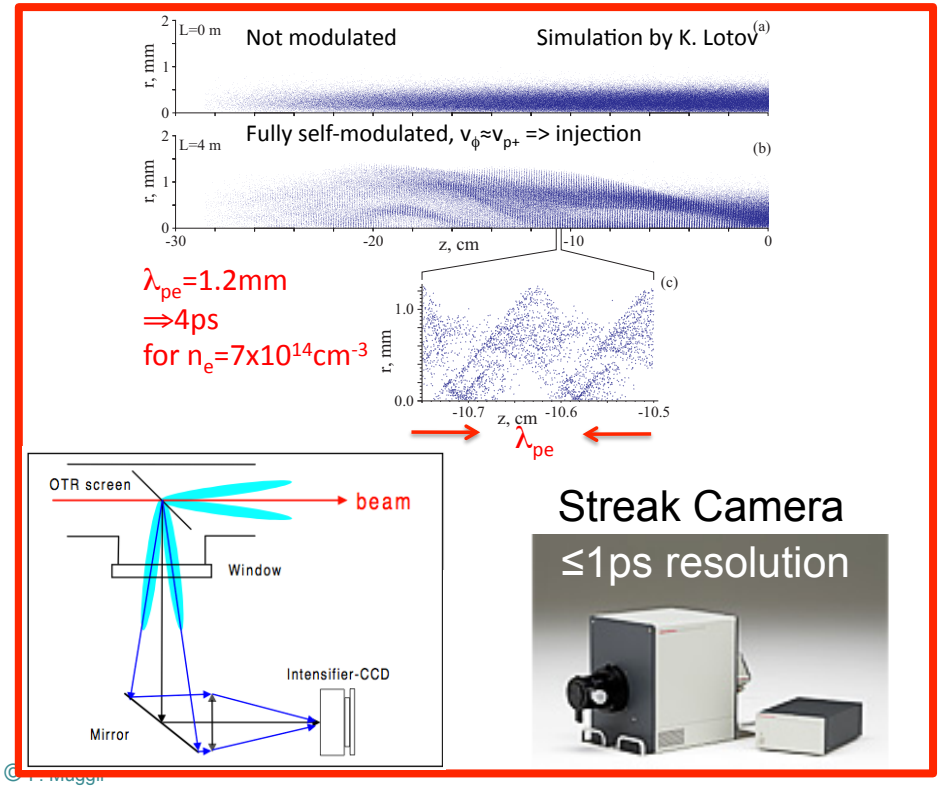
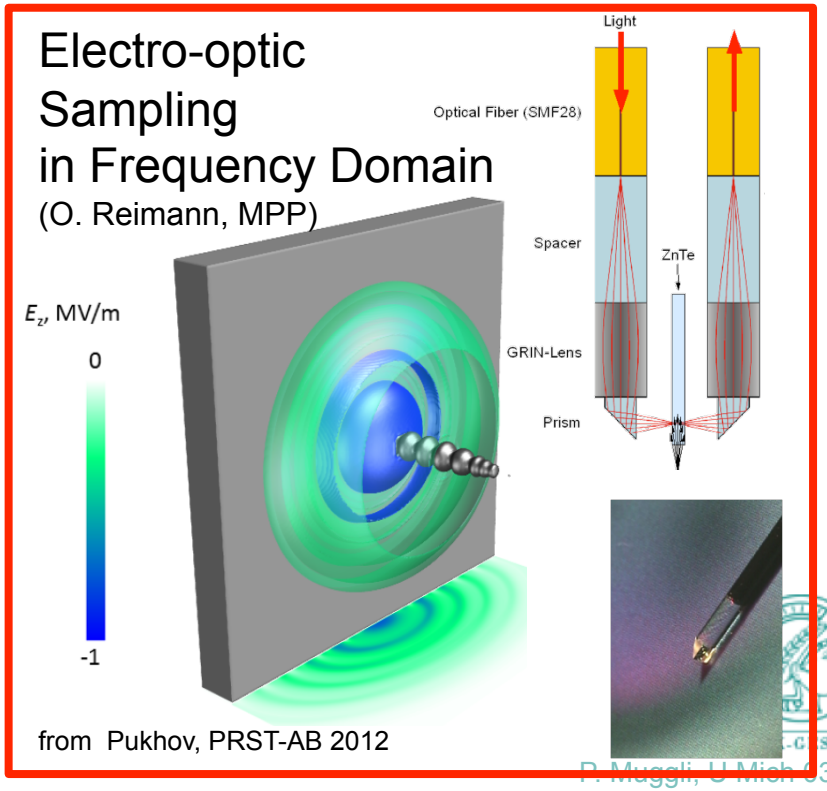
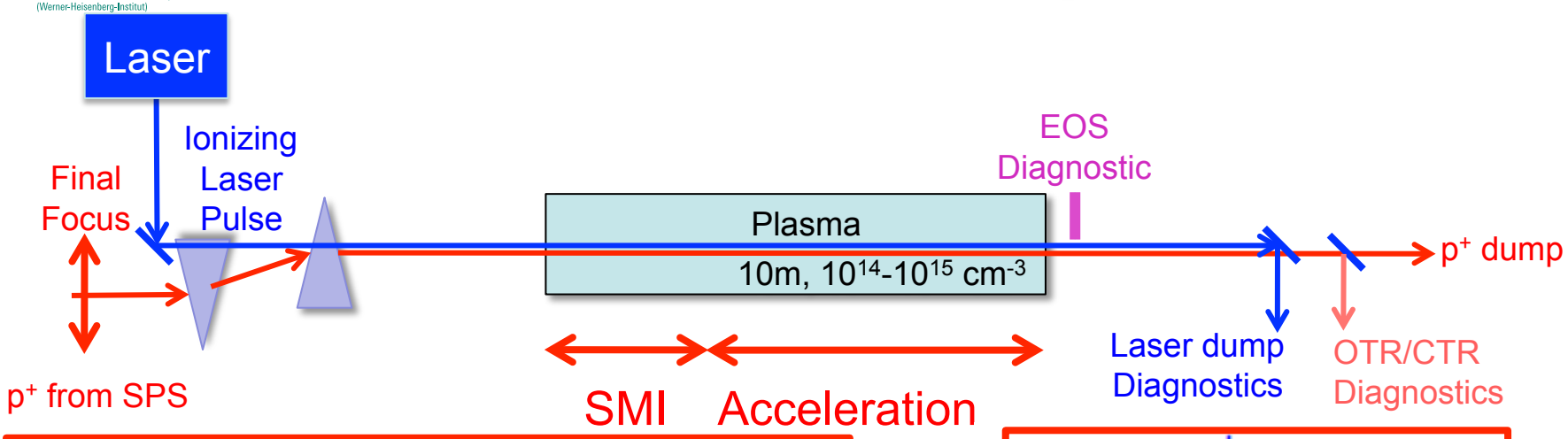
SMI DIAGNOSTICS

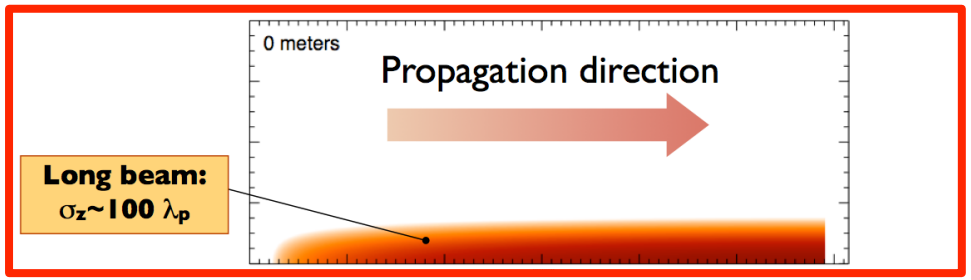






AWAKE EXPERIMENT @ CERN





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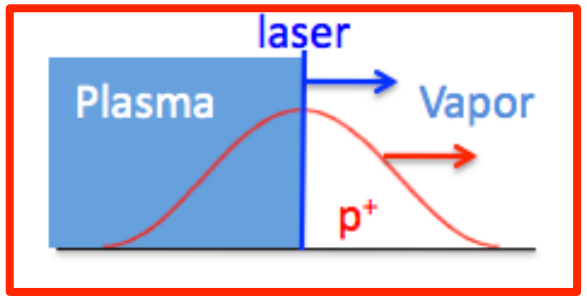
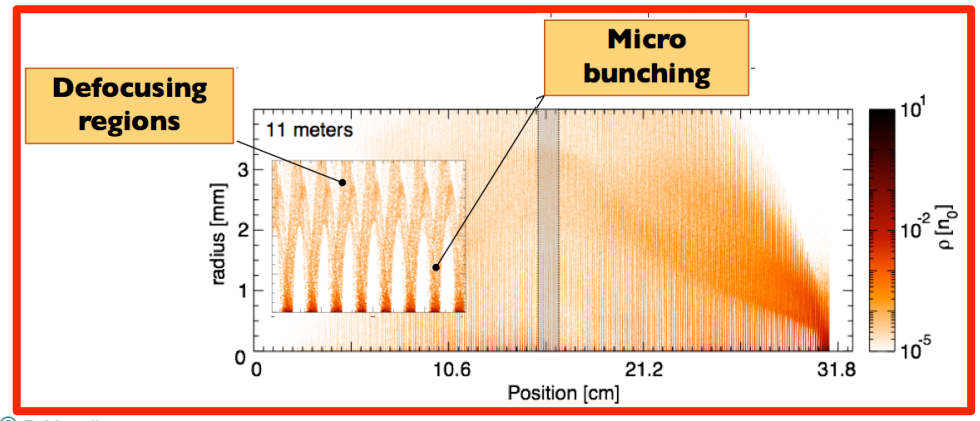


=

✧The SM p+ bunch resonantly drives wakefields



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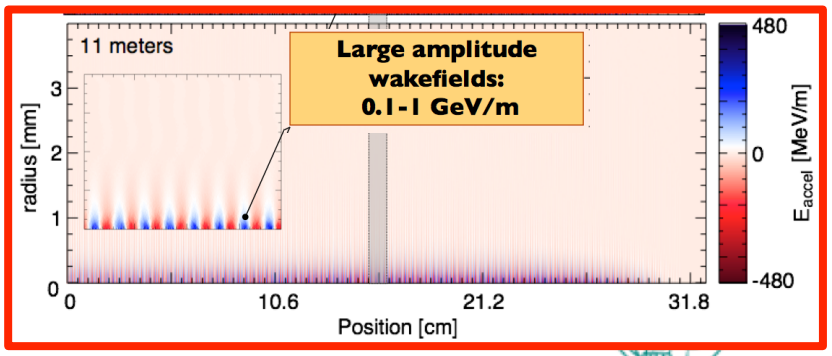

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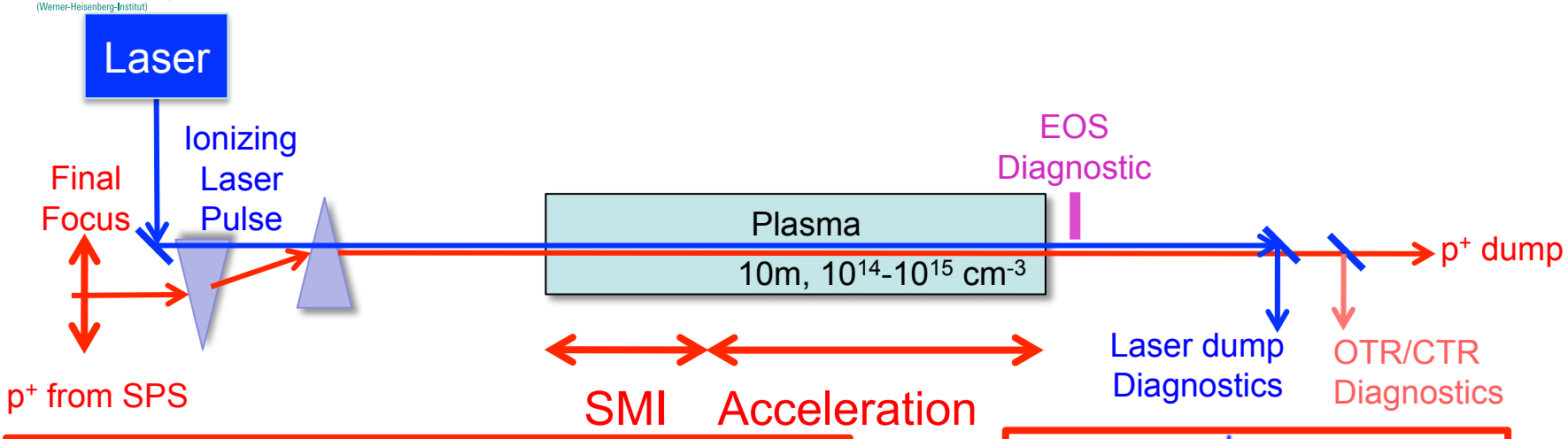
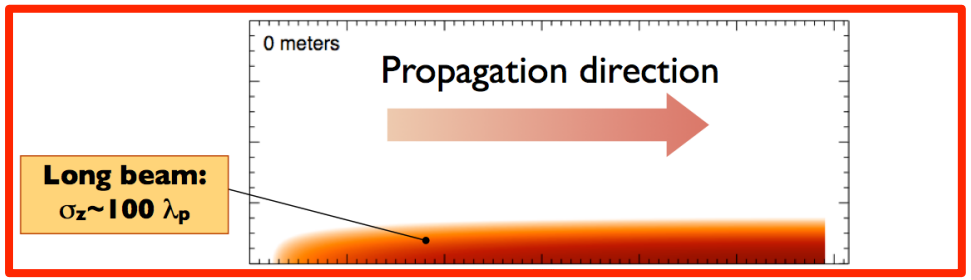
AWAKE EXPERIMENT @ CERN





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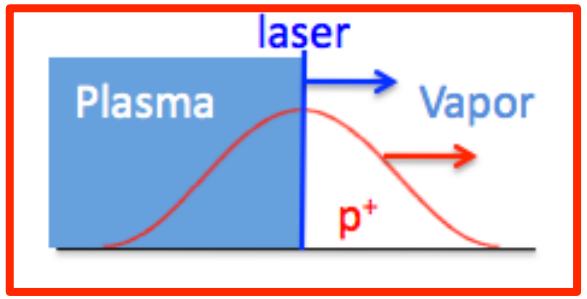
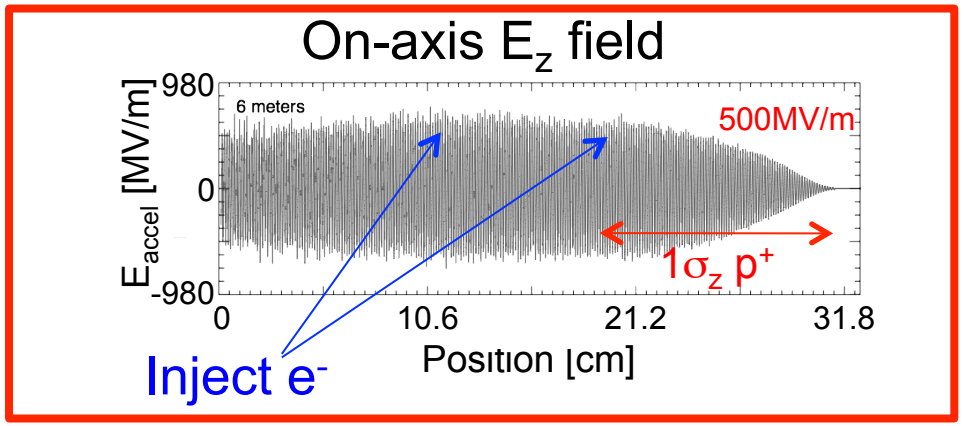


= ✧~GV/m accelerating field



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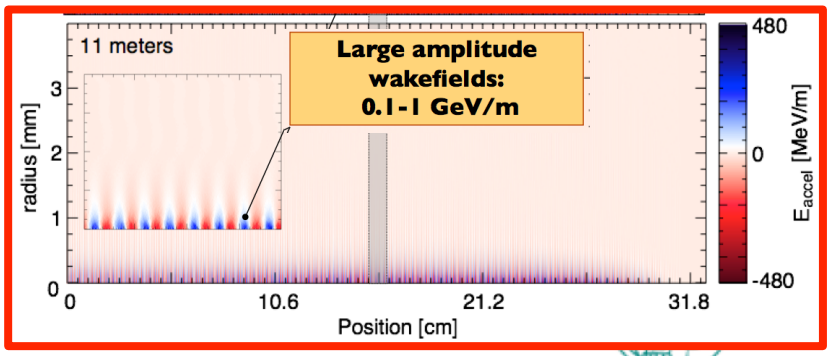

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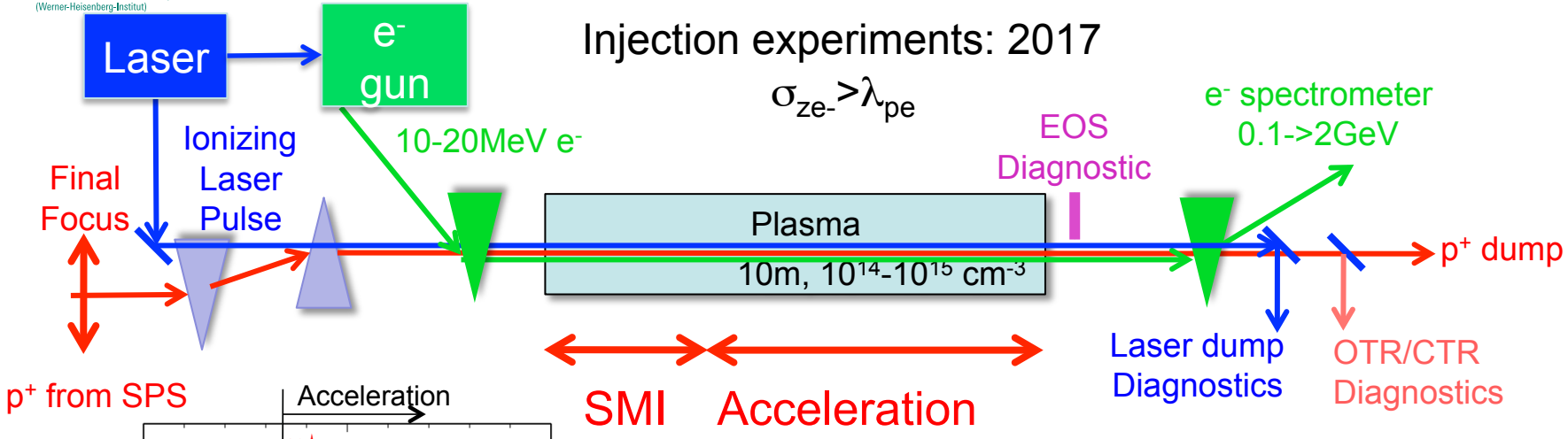
WAKEFIELDS SAMPLING / ACCELERATION

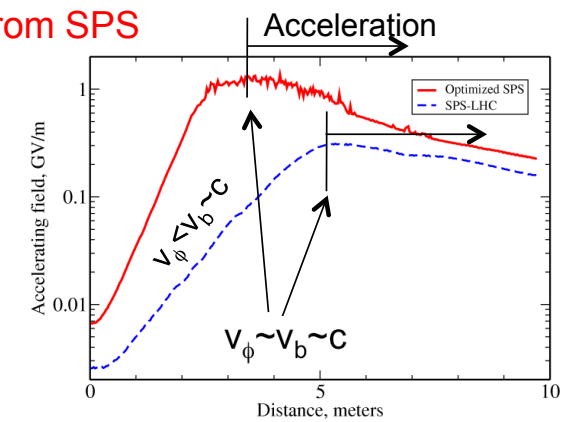
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

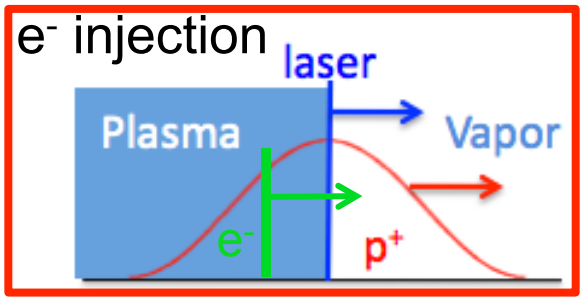
AWAKE

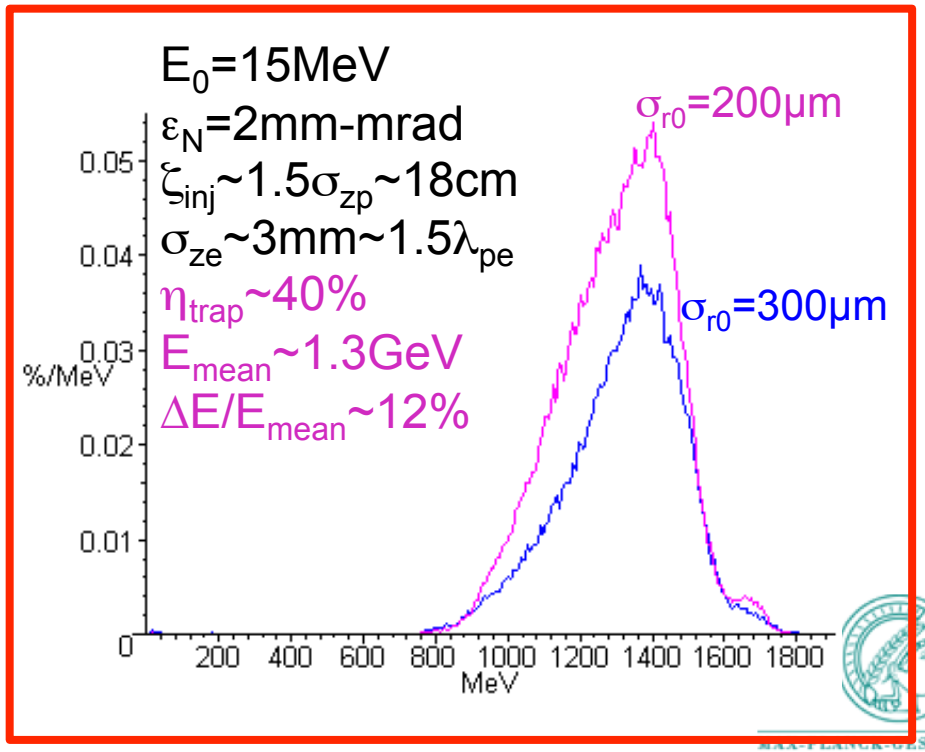
Injection experiments: 2017

$\sigma_{ze-} > \lambda_{pe}$









✧ Accelerate e⁻ to multi-GeV energies with ~GeV/m gradient

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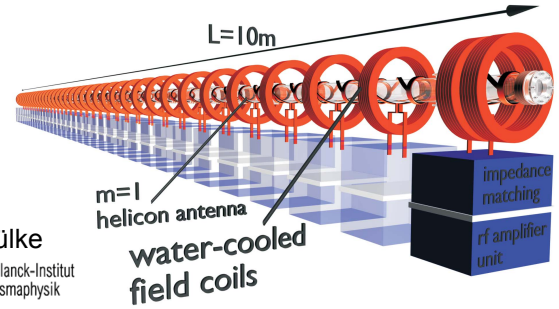
GOALS OF AWAKE EXPERIMENT

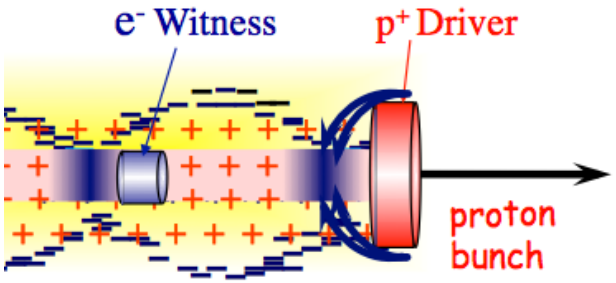
- ✧study the physics of p^+ bunch SMI (radial modulation, seeding, …)
- ✧probe the longitudinal (accelerating) wakefields with externally injected e^-
- ✧study injection dynamics (side or on-axis injection) of e^-
- ✧produce multi-GeV e^- with ~GV/m gradient maintained over m-distances
- ✧develop long,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

- ✧Experiment approved Fall 2013
  SMI experiments 2016
  e^- injection 2017



O. Grülke
Max-Planck-Institut für Plasmaphysik

- ✧Set-up a comprehensive and long term p^+-driven plasma-based accelerator program at CERN



- ✧Explore applications for a p^+-driven PWFA

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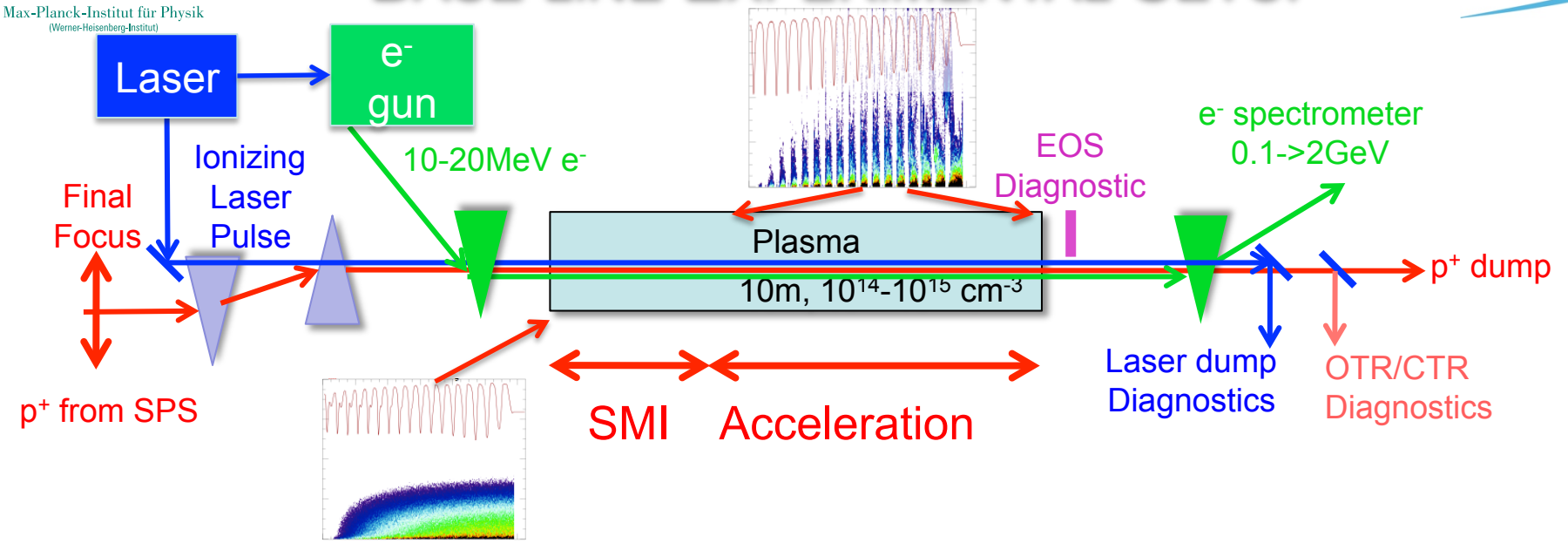
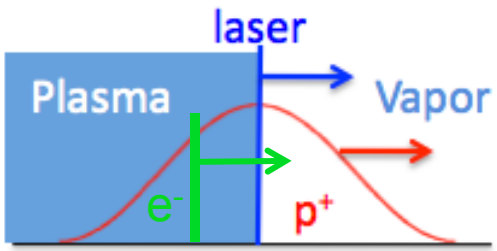
BASE-LiNE EXPERiMENTAL SETUP





- 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 plasma entrance ($\sigma_{ze-}>\lambda_{pe}$)
- 0.1-5GeV electron spectrometer
- OTR + streak camera, electro-optic sampling for p⁺-bunch modulation diag.

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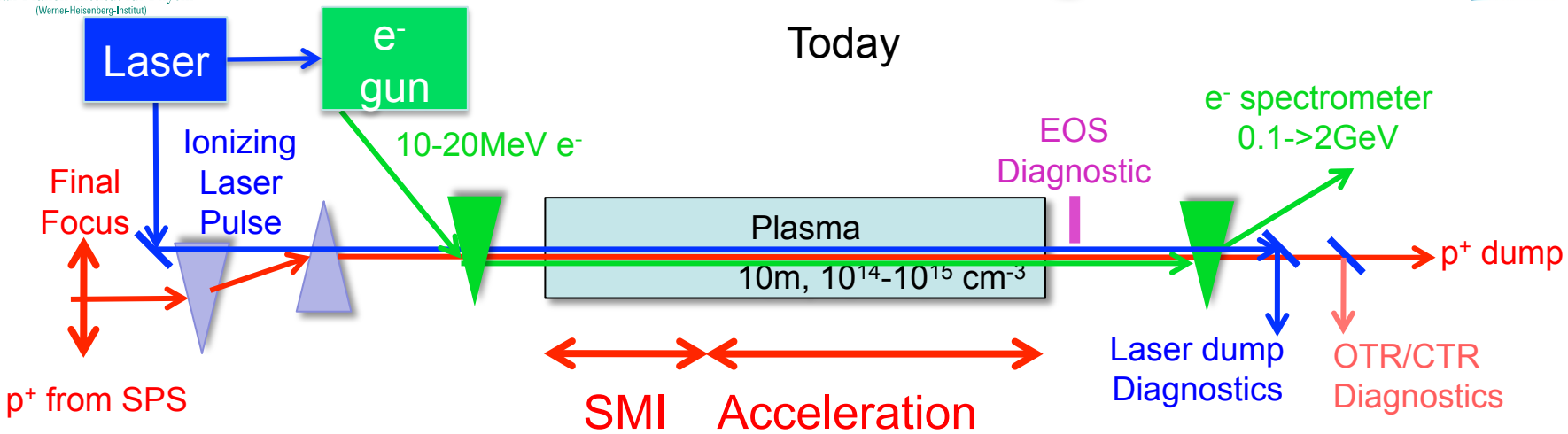
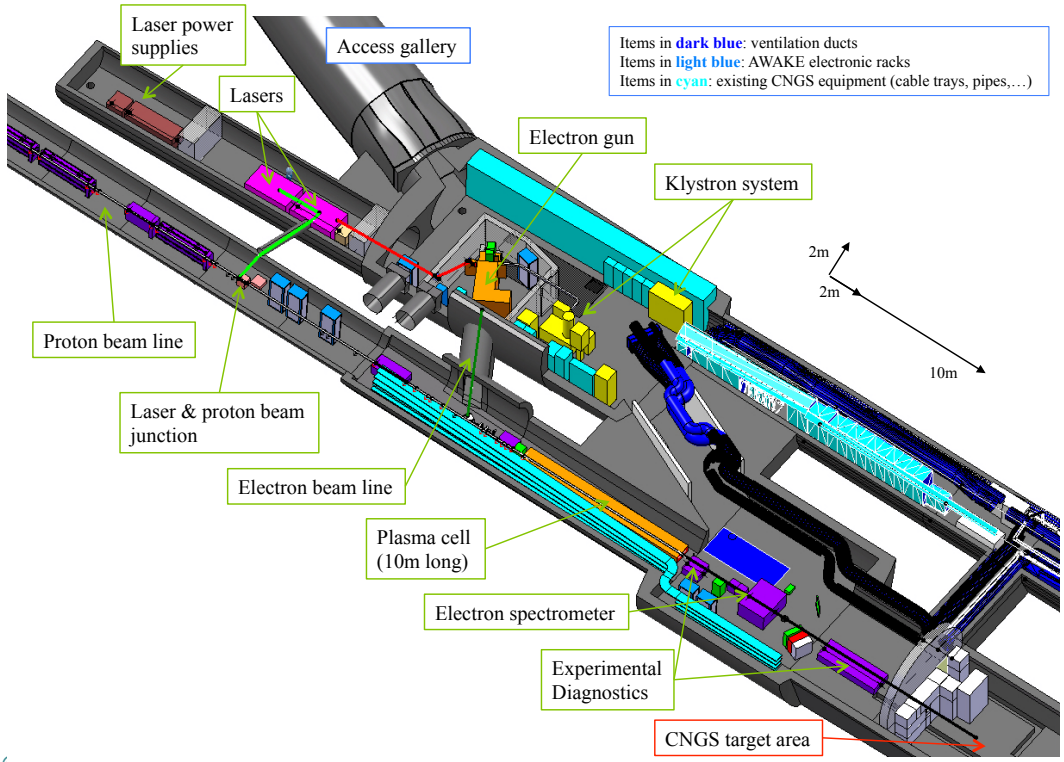
AWAKE EXPERIMENT @ CERN

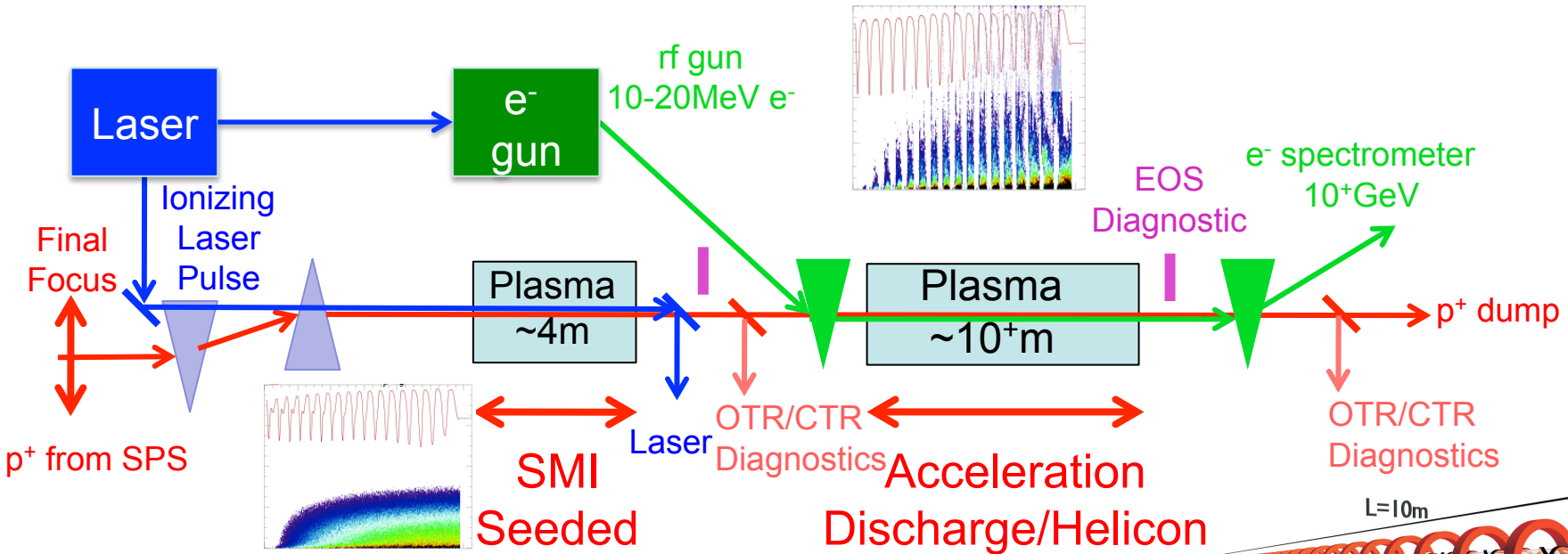
Today

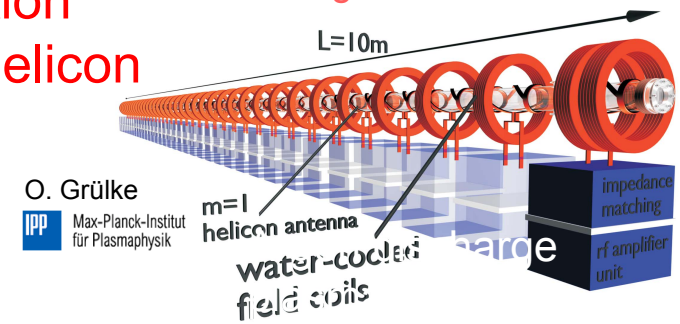




- CERN team already translated our dreams into CAD drawings
- Next step: make it real!

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 (scales to 100's m)
- ✧Inject short e⁻ bunch ($\sigma_z << \lambda_{pe}$)
- ✧Maybe able to tune plasma densities to maintain accelerating gradient

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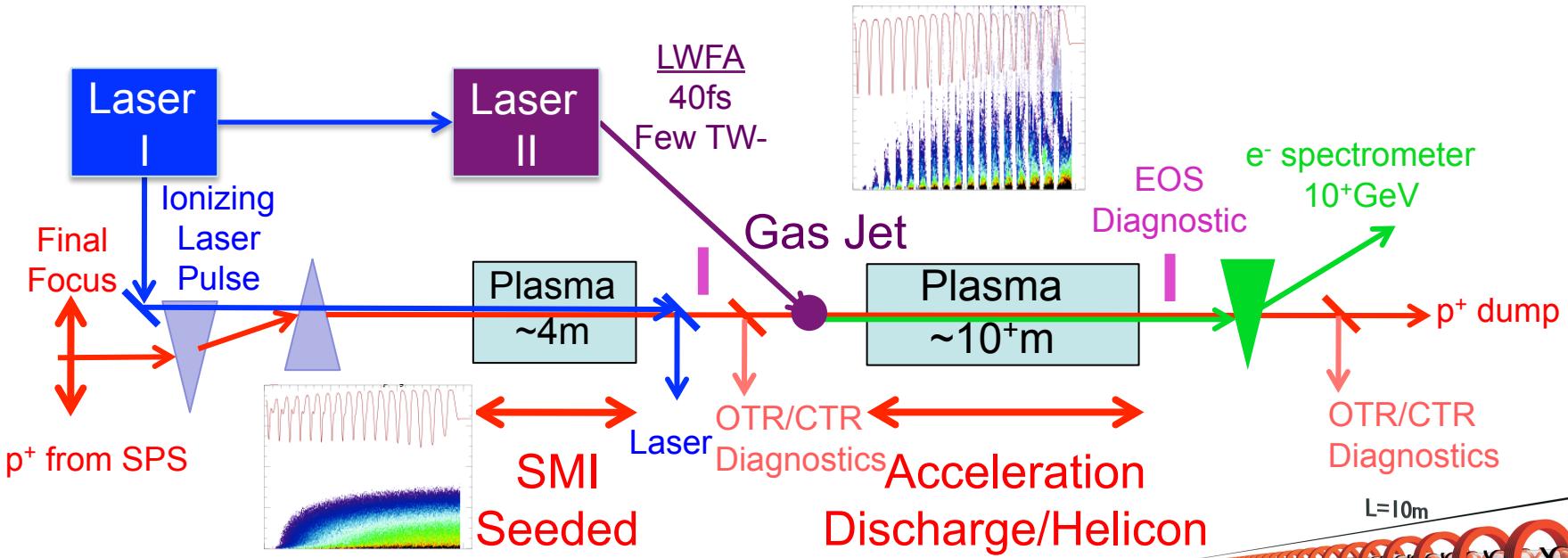
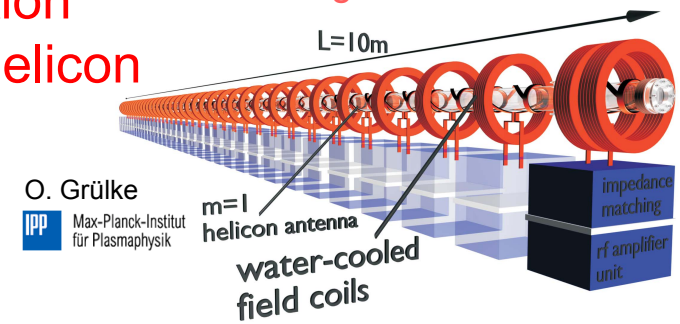
p⁺-PWFA ACCELERATOR PHYSICS





✧LWFA e⁻ injector: synchronization, short $\sigma_{ze-} << \lambda_p$, high-current (kA) bunch, beam loading...)

Muggli, IPAC'2014 Proceedings

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

OUTLINE

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

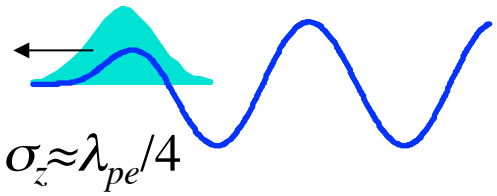
MAX-PLANCK-GESELLSCHAFT

~~4~~ 5 PLASMA ACCELERATORS*

- Plasma Wakefield Accelerator (PWFA)

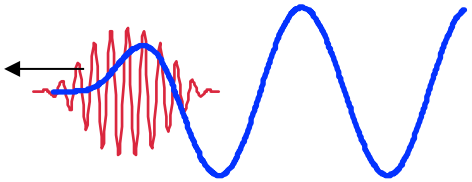
  A high energy particle bunch (e^-, e^+, ...)

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



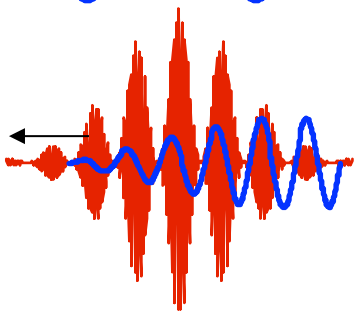
- Laser Wakefield Accelerator (LWFA)

  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)

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SUMMARY

- ✧ p^+ bunches: 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^+
  - Transverse modulation, large wakefields (~10GV/m), seeding (cut bunch), SMI/hosing competition, e^-/e^+ differences
  - Signs of radial modulation, energy loss, halo formation in two-day experiment!!!
- ✧ SMI PWFA experiments at CERN with p^+ (approved 2013, experiments 2016)
  - 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, CLARA-UK, INFN-Frascati, …)
- ✧ Simulations play a key role …

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Thank you to my collaborators!

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