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

AWAKE:

A Proof of Principle

Proton-driven, PWFA

R&D Experiment @ CERN

presented by:

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for the AWAKE Collaboration

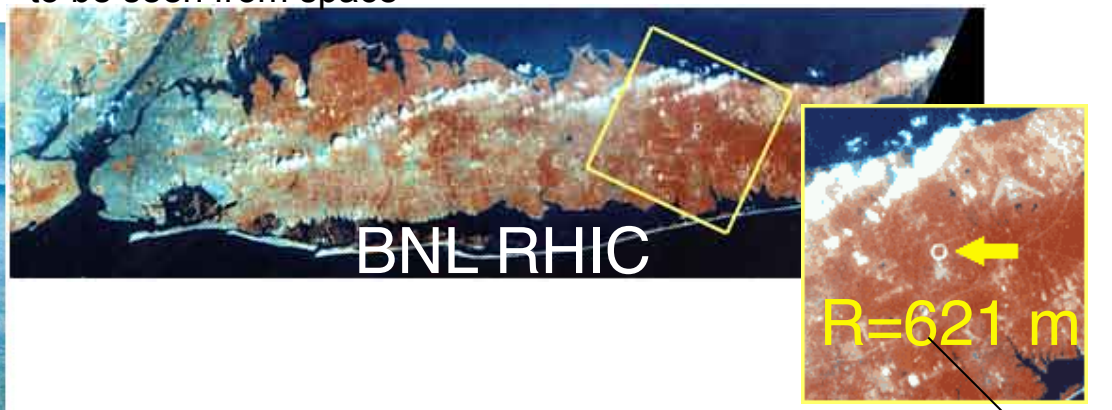
MAX-PLANCK-GESELLSCHAFT

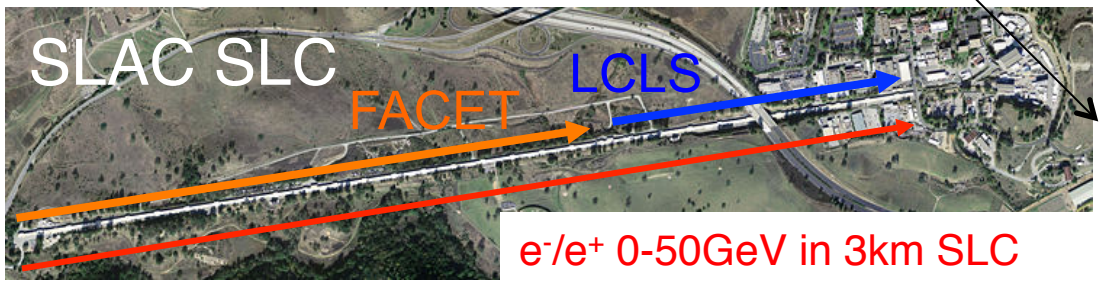
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

PARTICLE ACCELERATORS

AWAKE

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

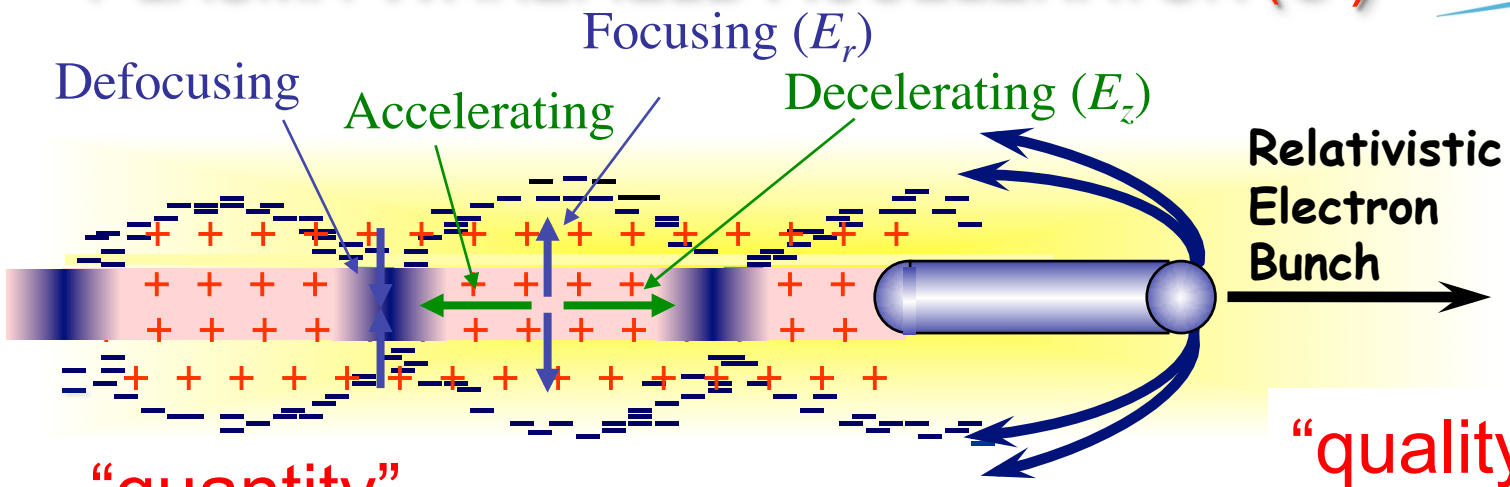




e^-/e^+ 0-50GeV in 3km SLC
e^-/e^+ 0-20GeV in 2km FACET
e^- 0-14GeV in 1km LCLS

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

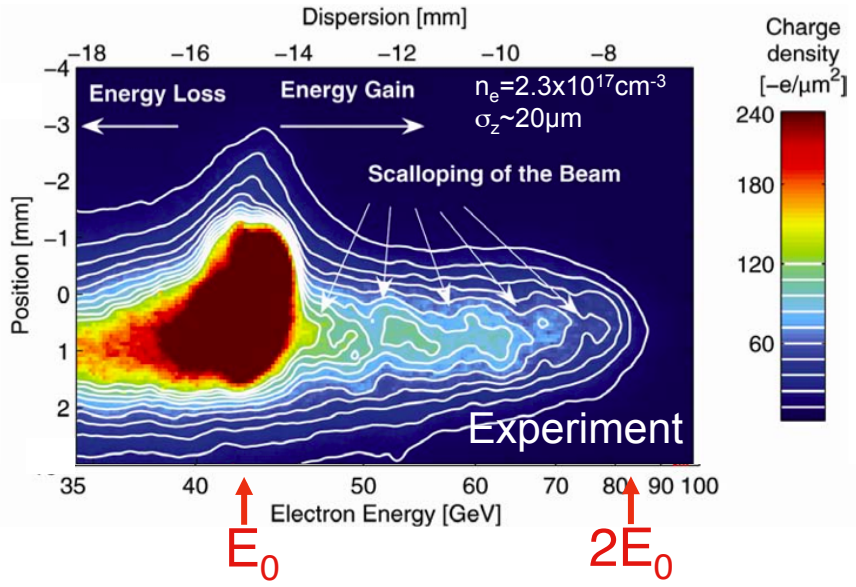
PLASMA WAKEFIELD ACCELERATOR (e^-)



"quantity"

"quality"

Blumenfeld, Nature 445, 741 (2007)

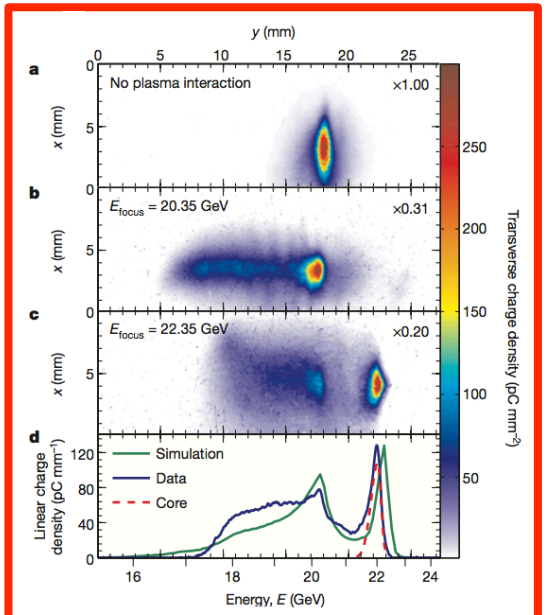


42 => 84GeV in 85cm! 50GeV/m

SLAC FACET

E200

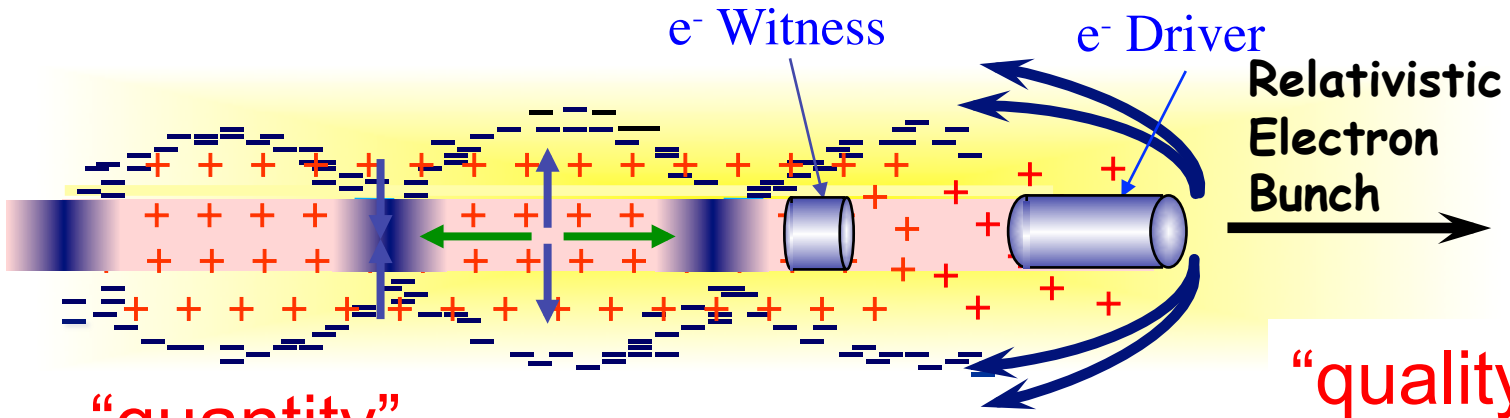
Litos, Nature 515(6) 92 (2014)



ΔE/E~%

η~30%

PLASMA WAKEFIELD ACCELERATOR (e^-)



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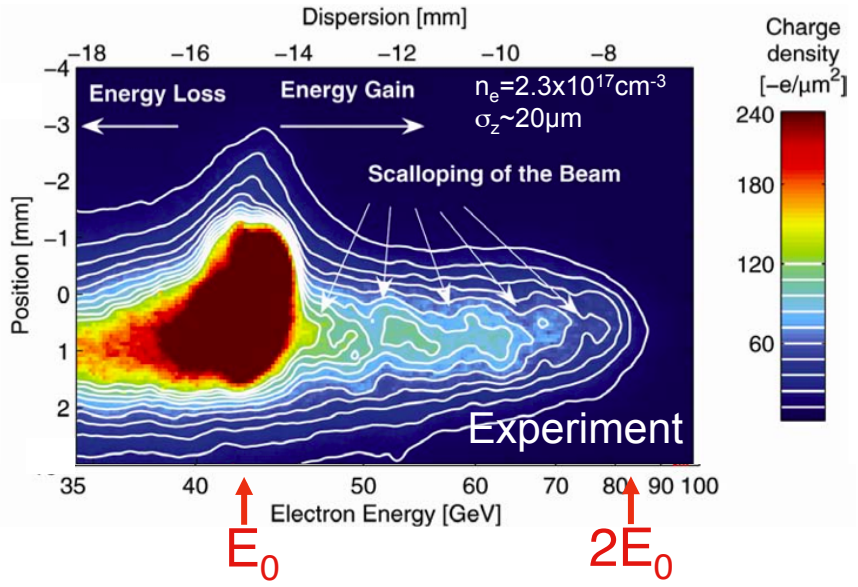

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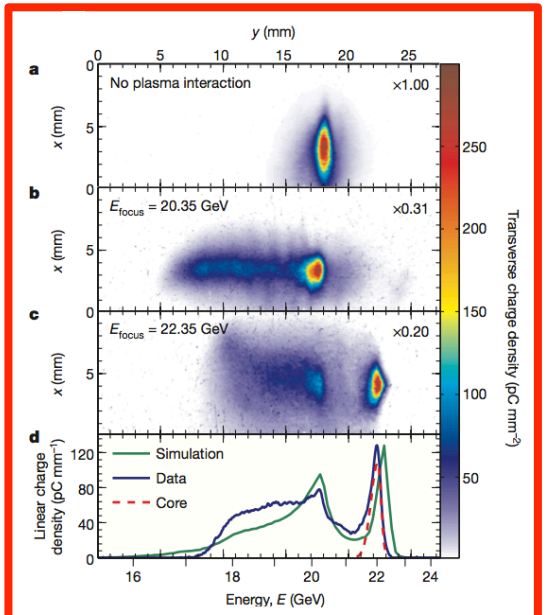

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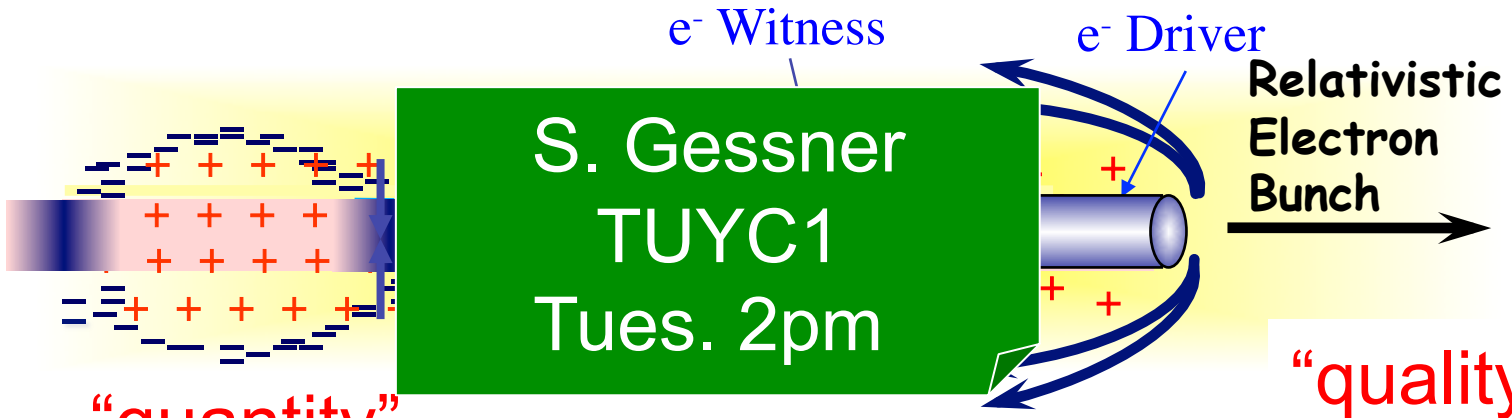

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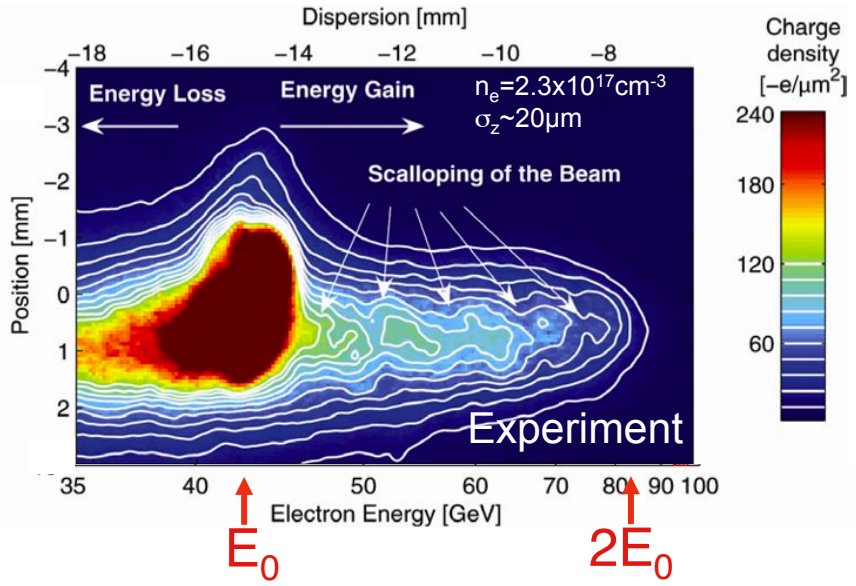

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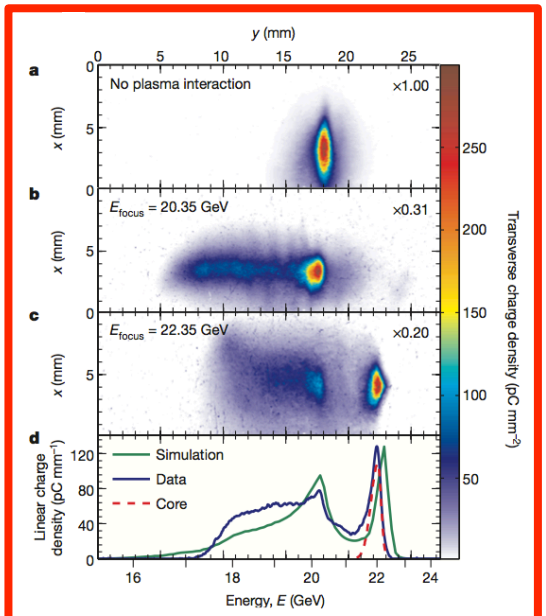


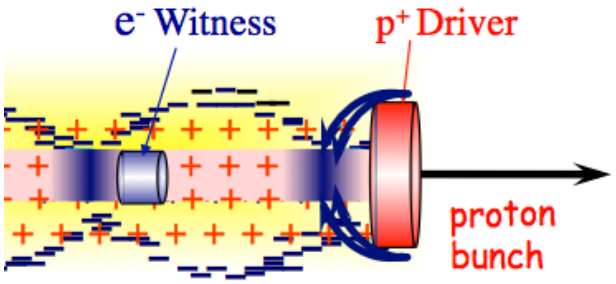
ΔE/E~%

η~30%

PROTON-DRIVEN PWFA

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

Blue. PRL 90, 214801 (2003)

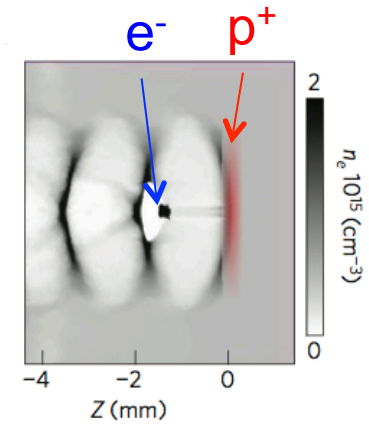


e^-: E_0=10GeV, $N=10^{10}$, W_0=16J

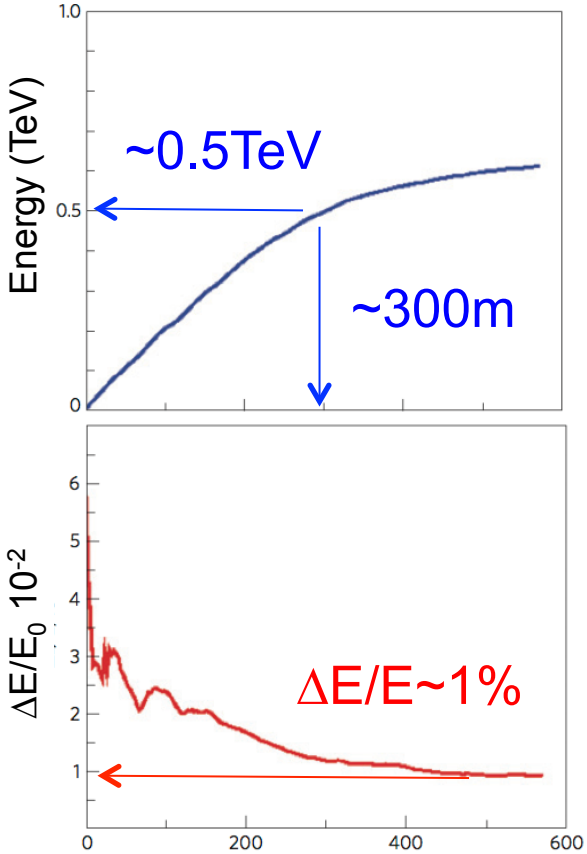
p^+: E_0=1TeV, σ_z=100µm, $N=10^{11}$, W_0=16kJ

Single Stage: W_f=1kJ

$n_e = 6\times10^{14}cm^{-3}$



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

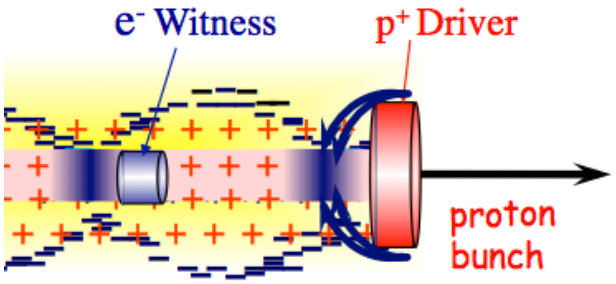


- Existing p^+ bunches carry 10's-100's kJ (>>e^- bunches)
- Accelerate an e^- bunch on the wakefields of a p^+ bunch
- Single stage, no gradient dilution
- Gradient ~1 GV/m over 100's m
- Operate at lower n_e ($6\times10^{14}cm^{-3}$), larger $(\lambda_{pe})^3$, easier life …

PROTON-DRIVEN PWFA

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

Blue. PRL 90, 214801 (2003)



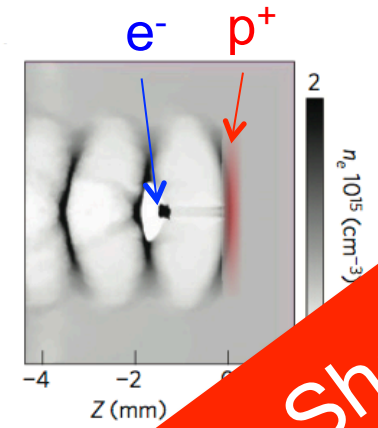
e^-: E_0=10GeV

p^+: E_0=1T

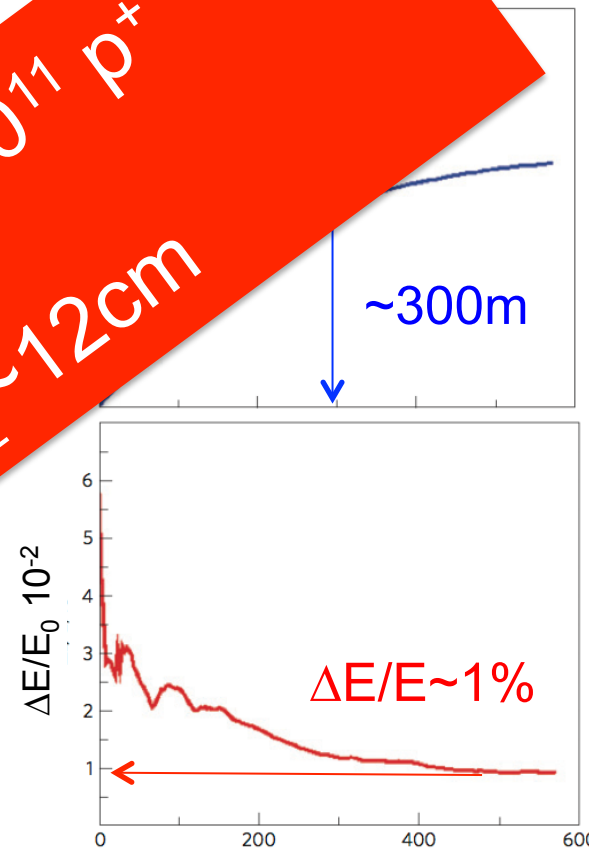
$N=10^{10}$

W_0=

Single Stage



		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

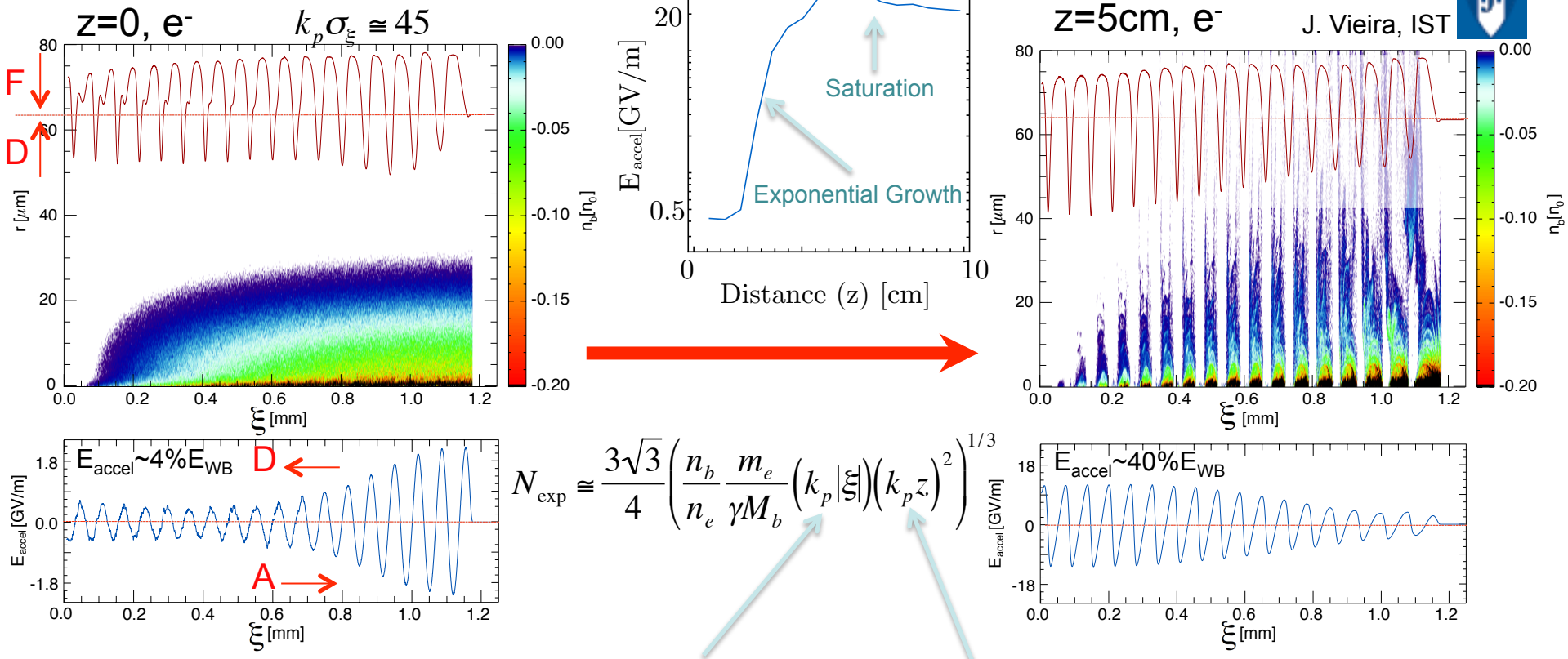


Short (100μm) bunches with 10^{11} p^+ do not exist!!!

CERN PS-SPS-LHC σ_z~12cm

- E… 10's-100's kJ (>>e^- bunches)
- …n on the wakefields of a p^+ bunch
- Si… gradient dilution
- Grad… GV/m over 100's m
- Operat… at lower n_e ($6\times10^{14}cm^{-3}$), larger $(\lambda_{pe})^3$, easier life …

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

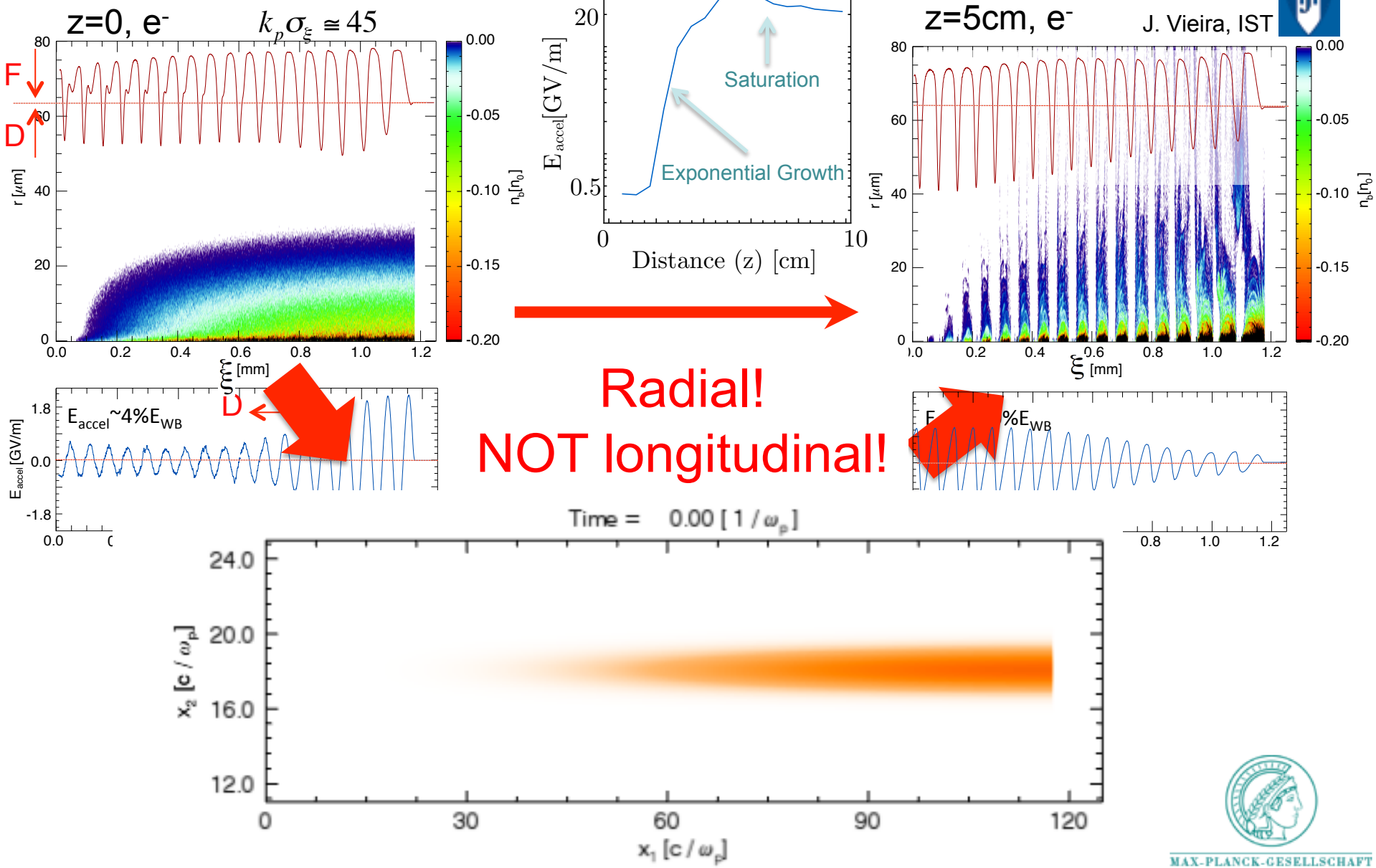
Pukhov et al., PRL 107, 145003 (2011)
Schroeder et al., PRL 107, 145002 (2011)

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

*Kumar, PRL 104, 255003 (2010)

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

SELF-MODULATION INSTABILITY (SMI)



SELF-MODULATION INSTABILITY (SMI)

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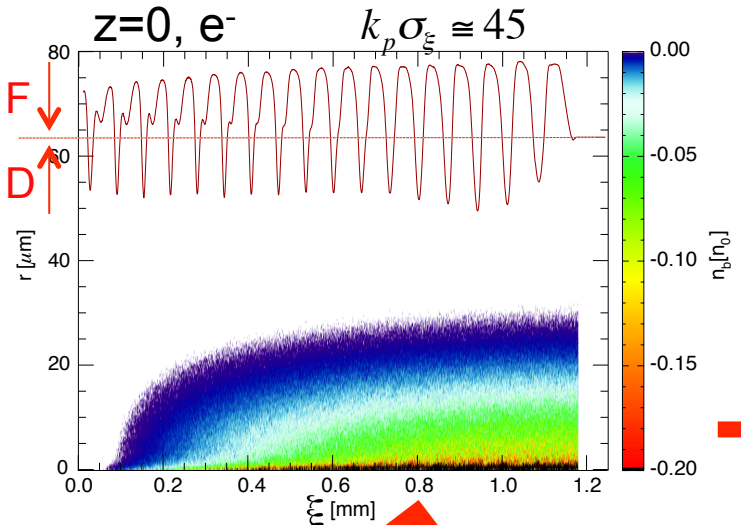

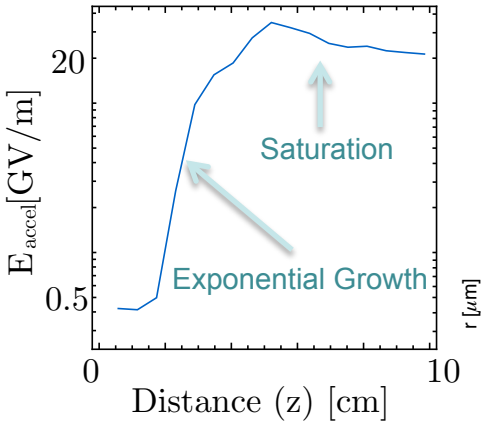

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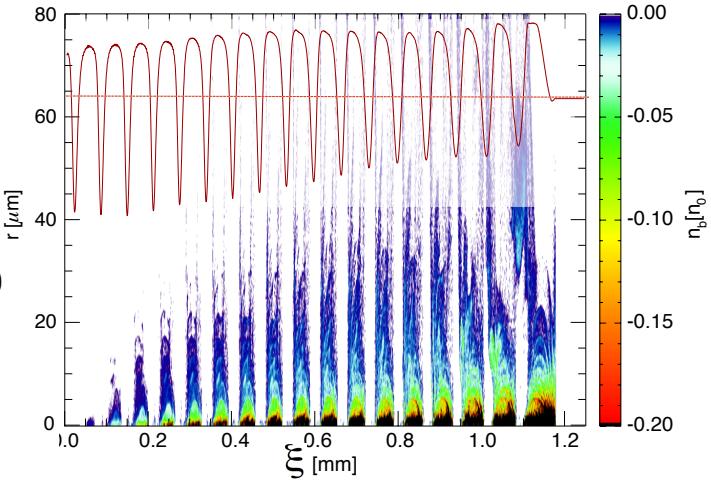
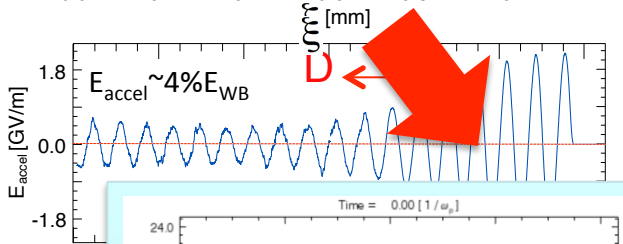
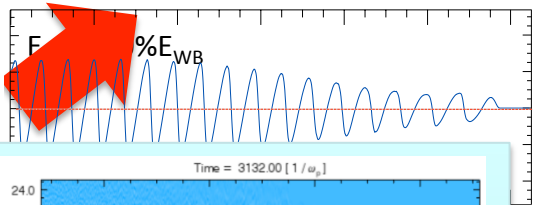
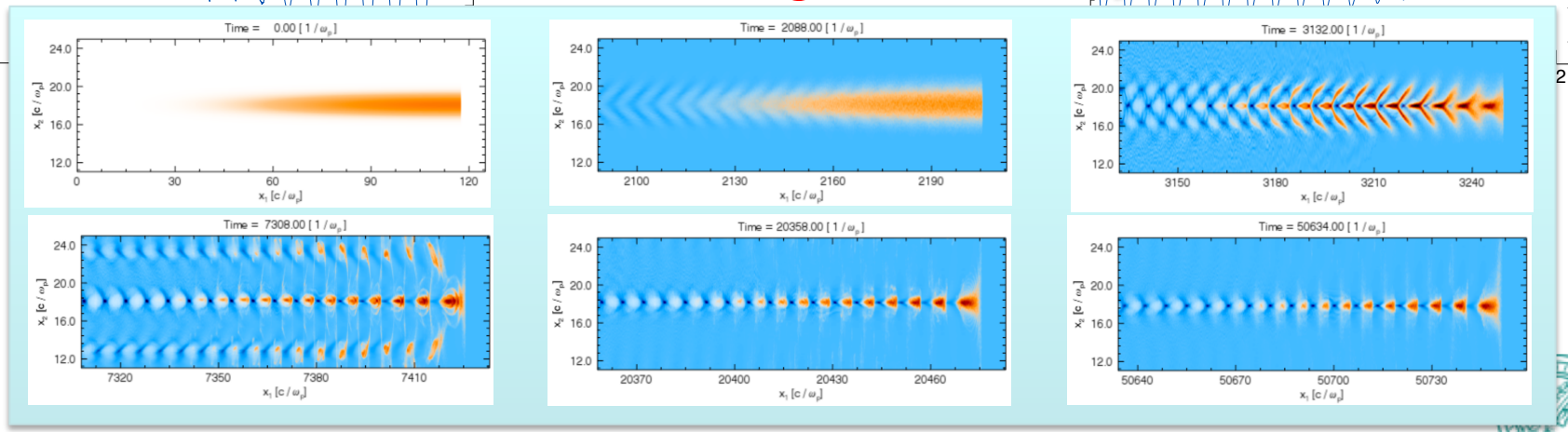




Radial!

NOT longitudinal!





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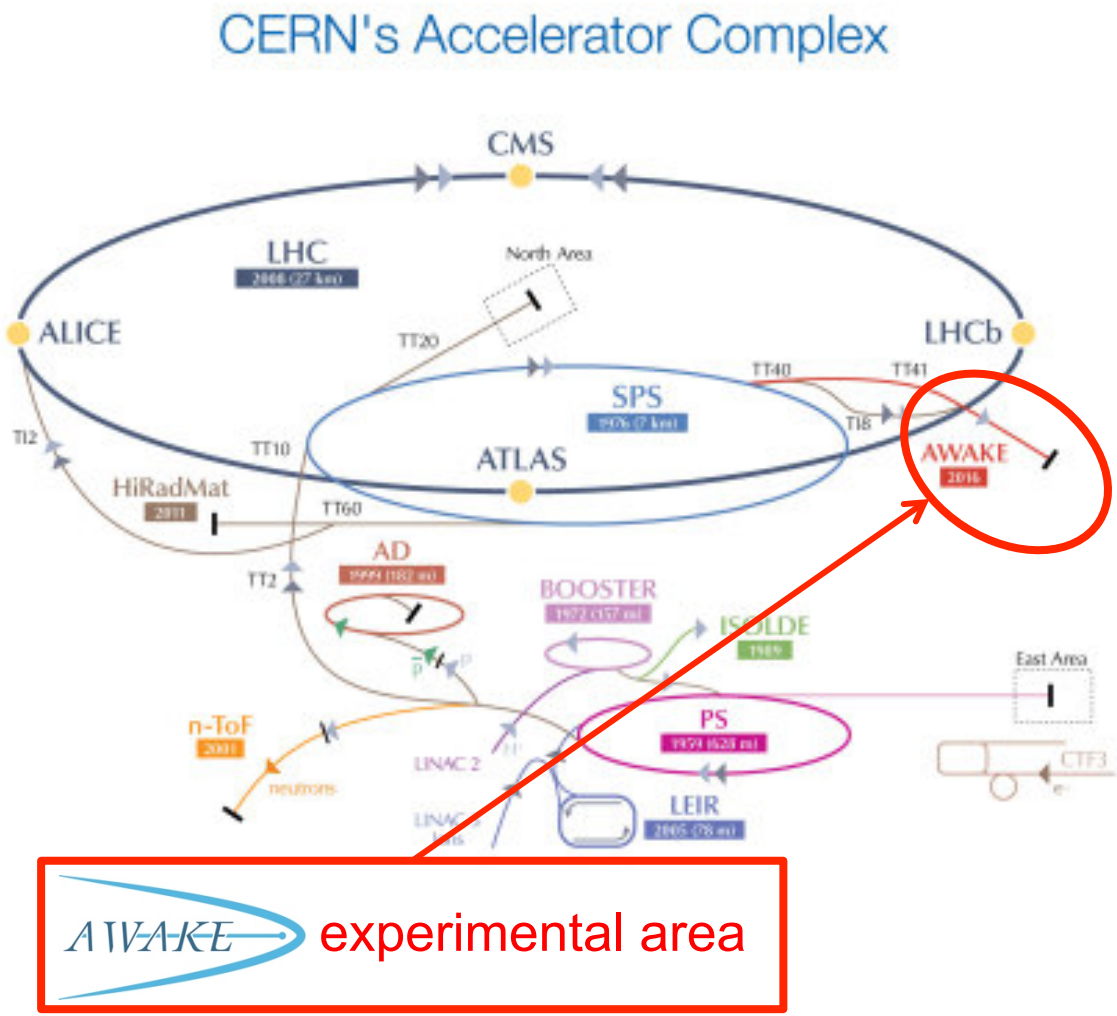
PROTON BEAMS @ CERN



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

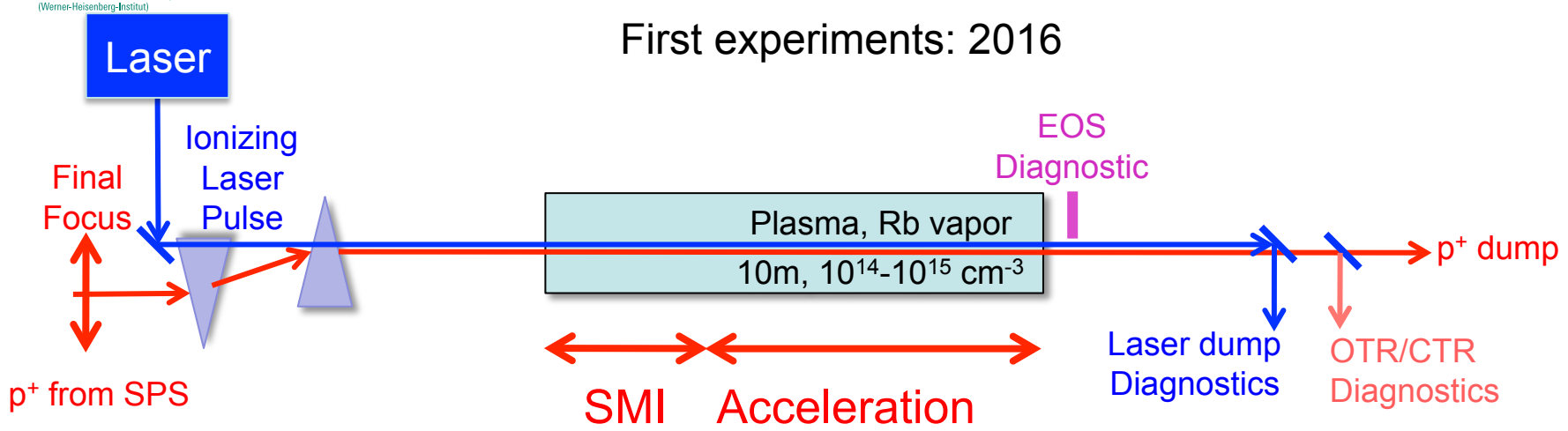
Plasma: $n_e \sim 7 \times 10^{14} cm^{-3}$ for $k_p \sigma_r \approx 1$
$\lambda_{pe} \sim 1.3mm << \sigma_z$
$f_{pe} \sim 240GHz$
$L_p \sim 10m \sim 2\beta^*$

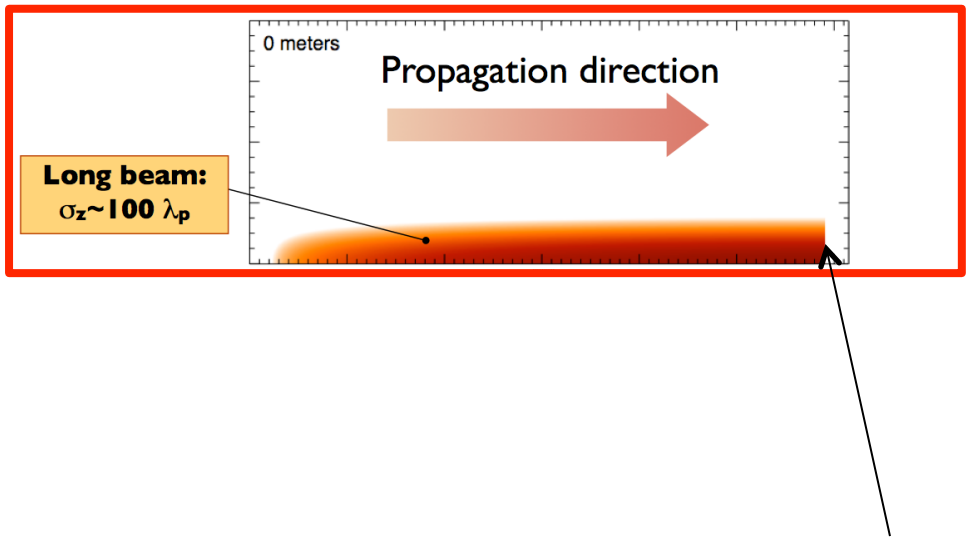
✧SPS beam: high energy, small σ_r^*, long β^*

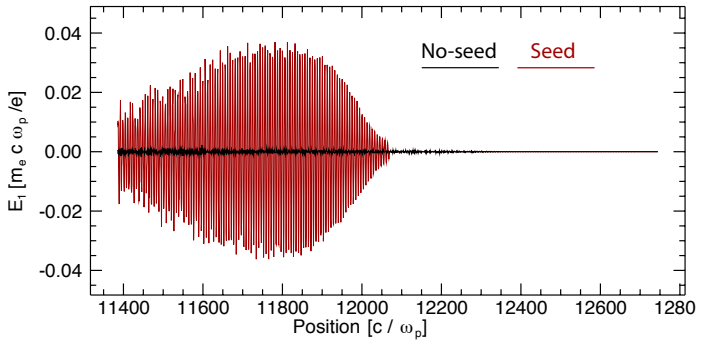
AWAKE Collaboration, Plasma Phys. Control. Fusion 56 084013 (2014)

AWAKE Experiment @ CERN

First experiments: 2016





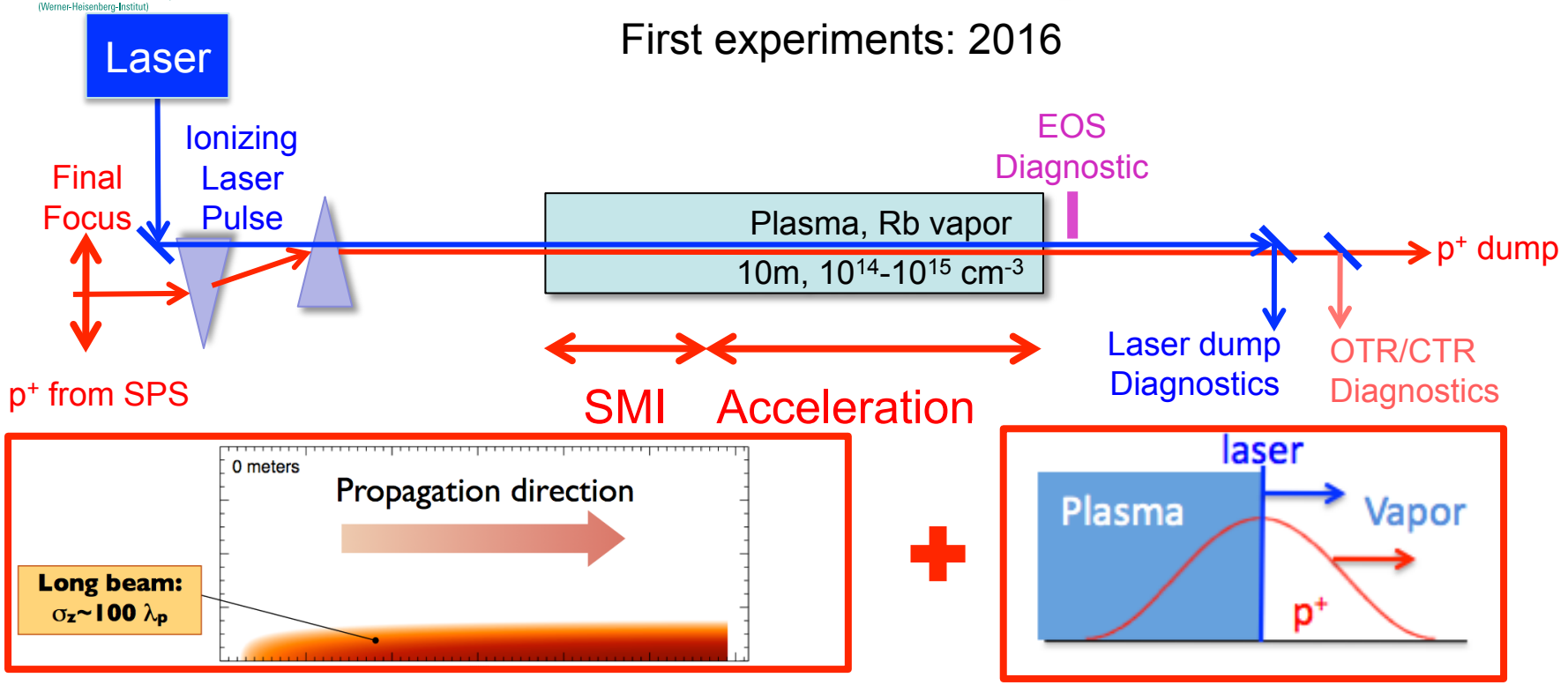


✧No seed no SMI (over 10m)

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

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~7x10^{14}cm^{-3}) => Self-modulation Instability (SMI)*
- $\sigma_{z\ laser}$~30μm(100fs)<<λ_{pe} => good seed

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

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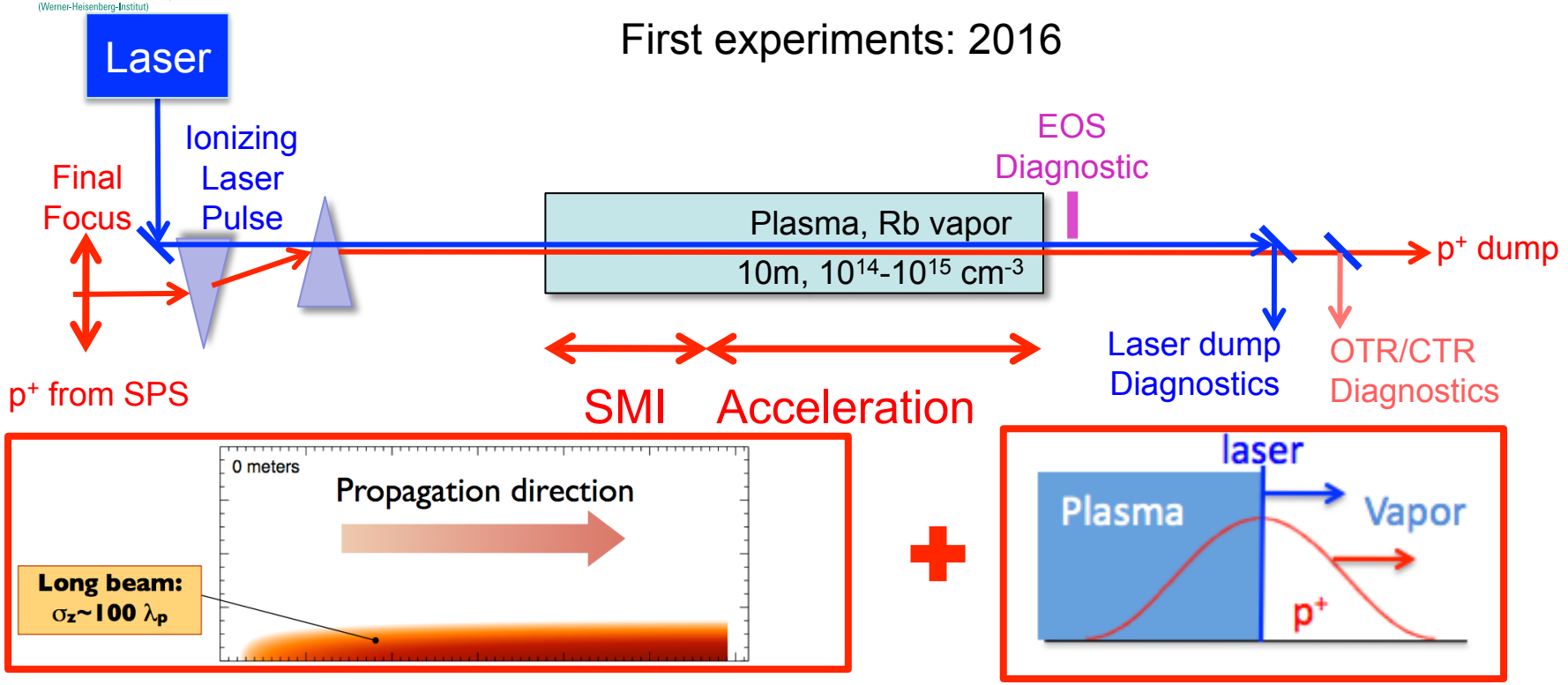

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J. T. Moody
WEPWA047

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

AWAKE EXPERIMENT @ CERN

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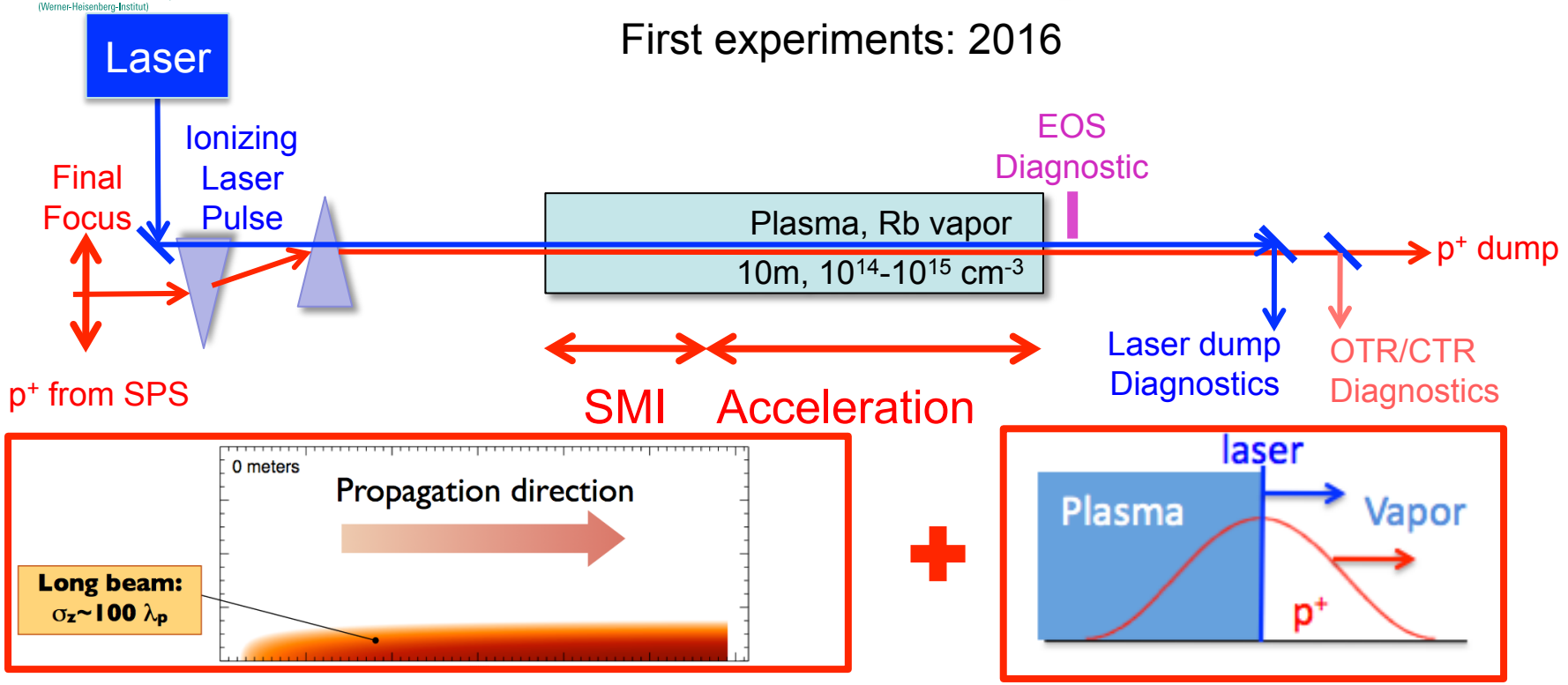

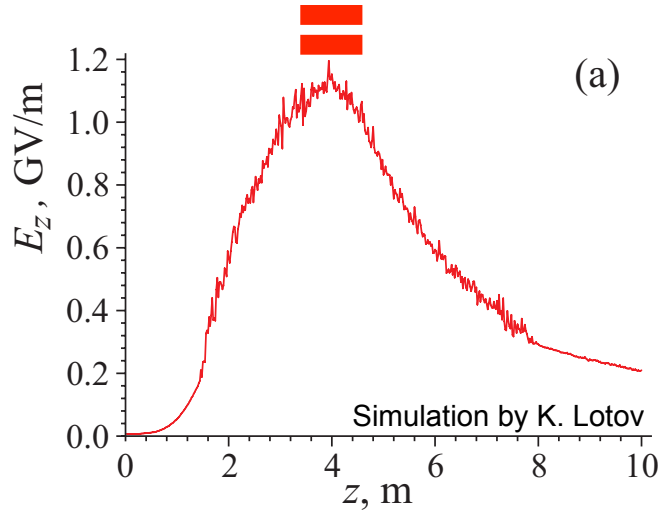

✧ The wakefields grow …

AWAKE EXPERIMENT @ CERN

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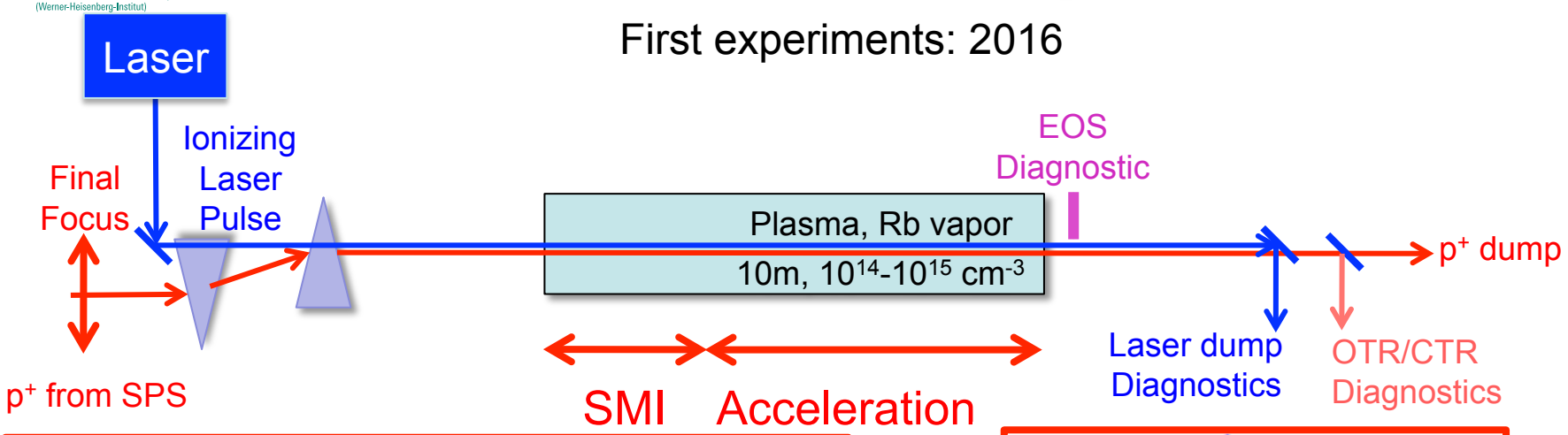
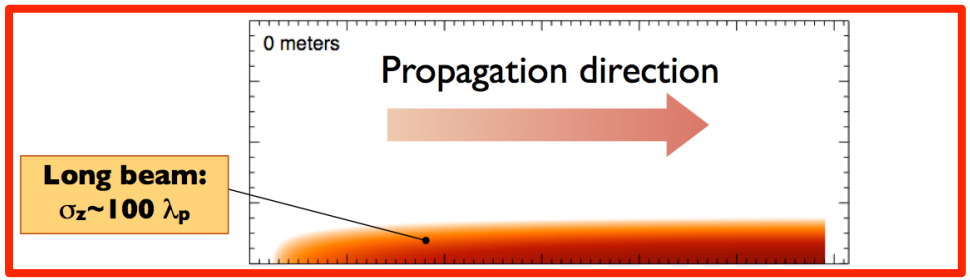
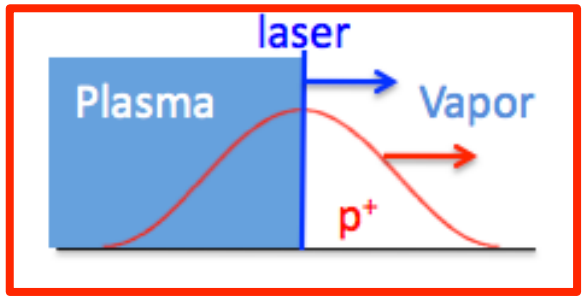
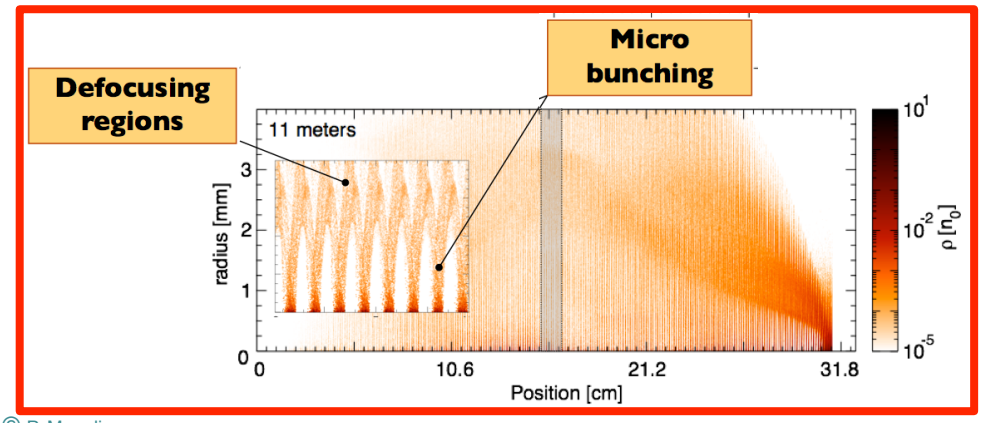








- The long (σ_z~12cm) p^+ bunch self-modulates with period λ_{pe}~1.2mm (n_e~7x10^{14}cm^{-3})

SMI DIAGNOSTICS

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

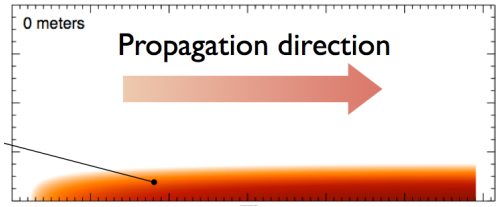
AWAKE

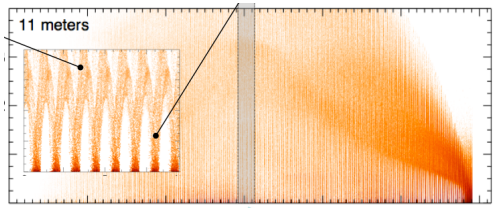
2016

Laser

Ionizing Laser Pulse

Final Focus





EOS Diagnostic

Plasma, Rb vapor
10m, 10^{14}-10^{15} cm^{-3}

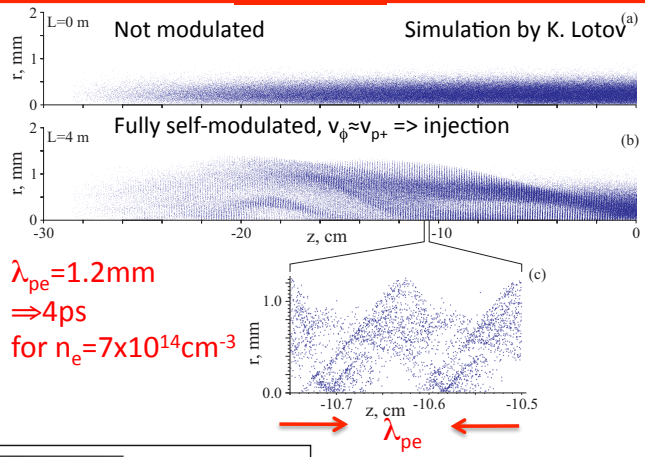
p^+ dump

OTR/CTR Diagnostics

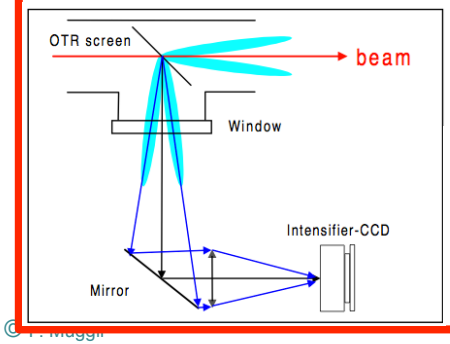
p^+ from SPS

SMI Acceleration

OTR

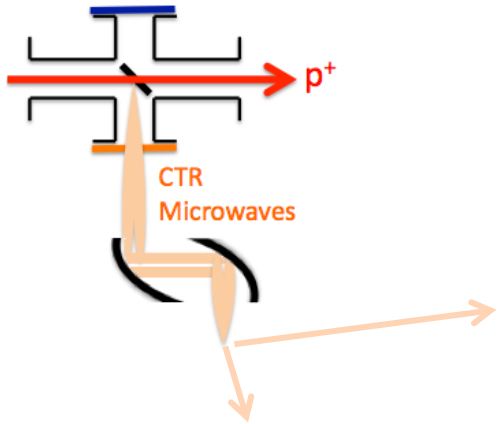


λ_{pe}=1.2mm
⇒4ps
for n_e=7x10^{14}cm^{-3}

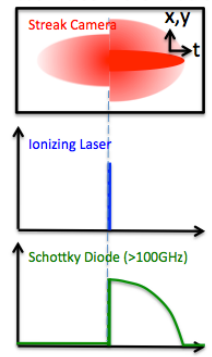


Streak Camera
≤1ps resolution

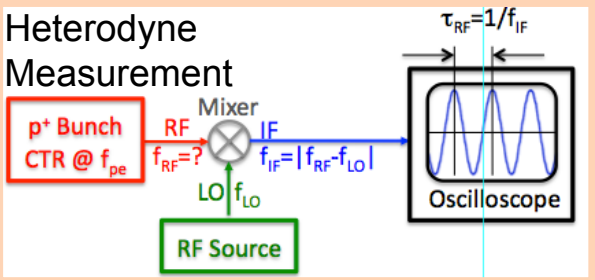
CTR



Schottky Diode

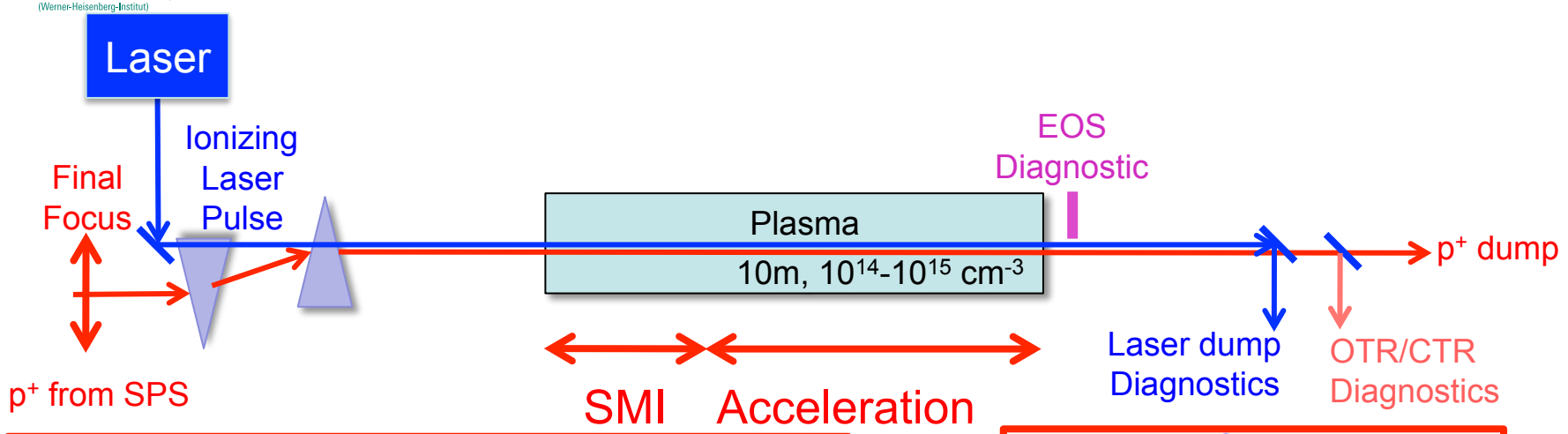


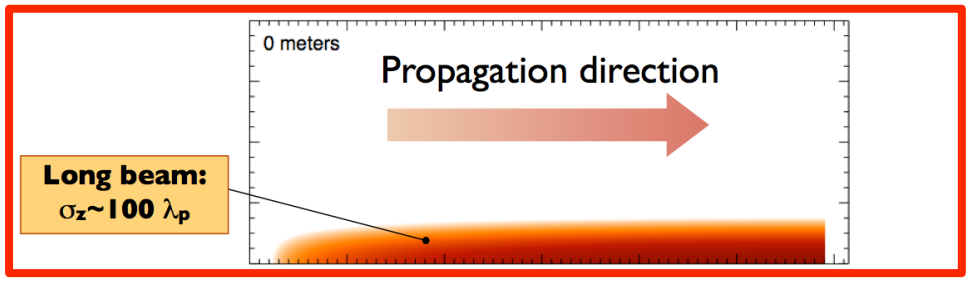
Heterodyne Measurement

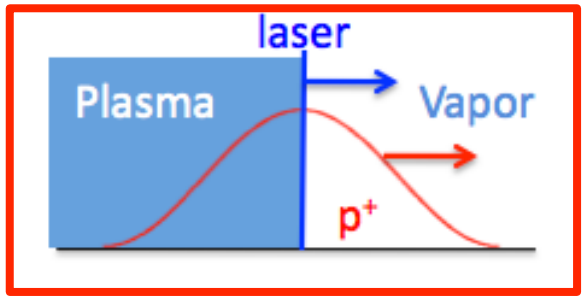


MAX-PLANCK-GESELLSCHAFT

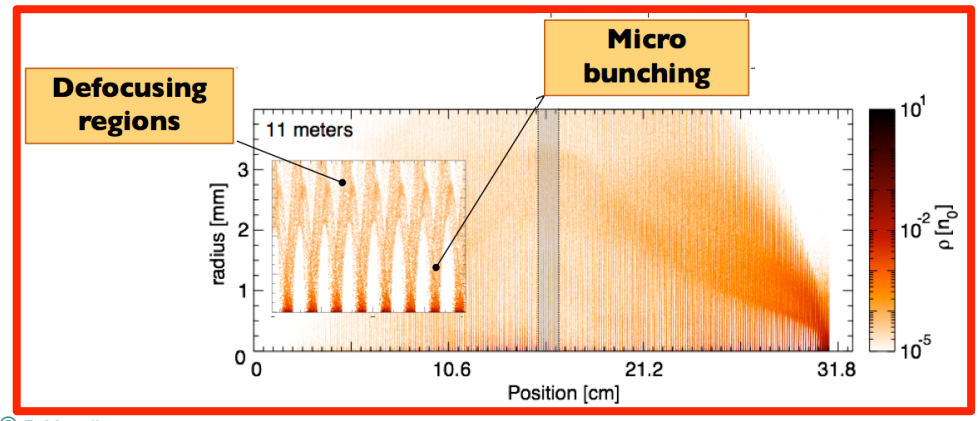
AWAKE Experiment @ CERN

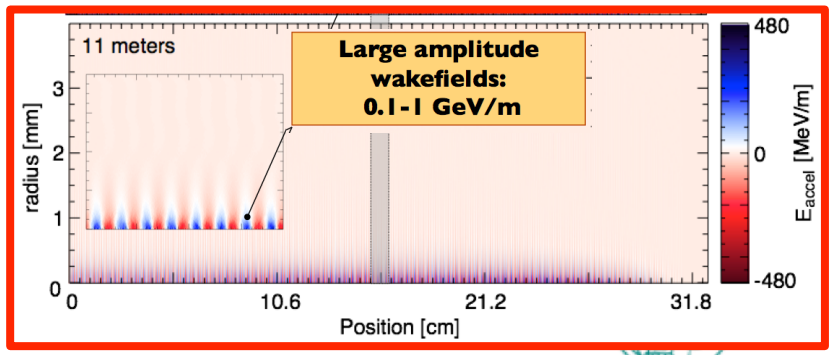




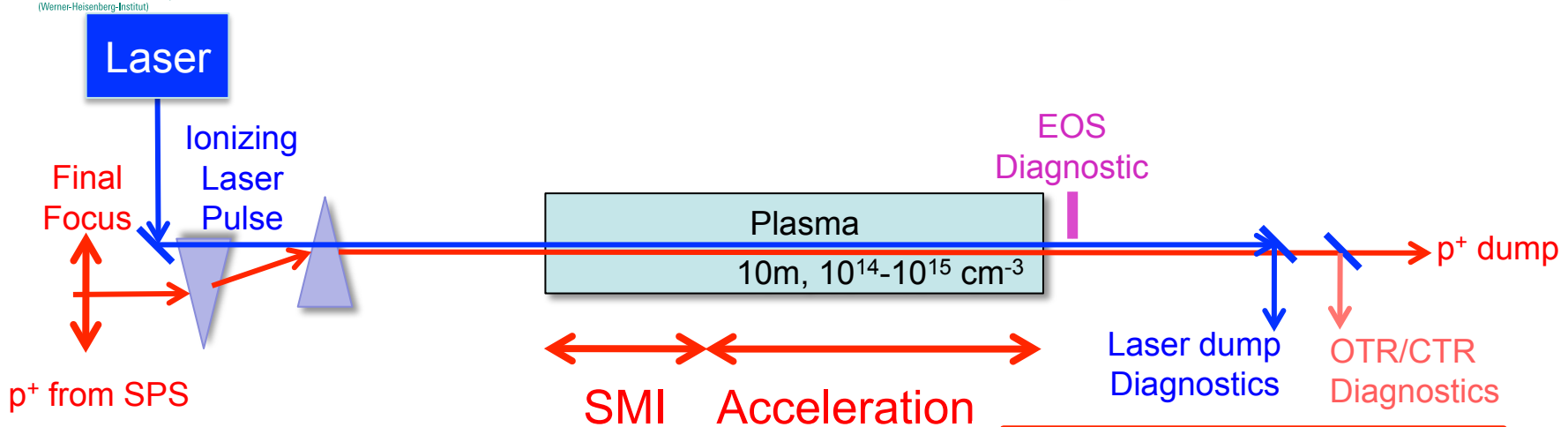


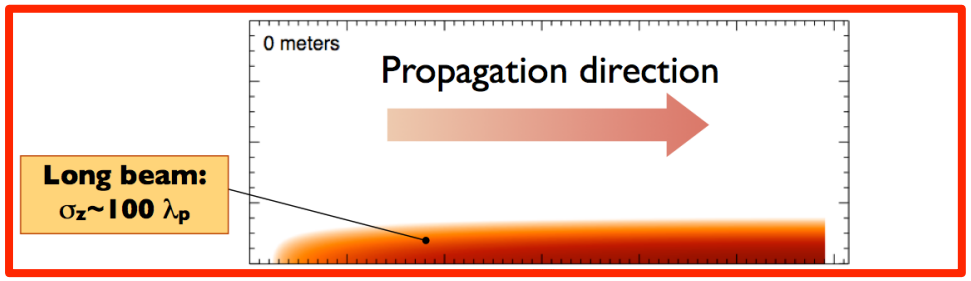
✧The SM p^+ bunch resonantly drives wakefields

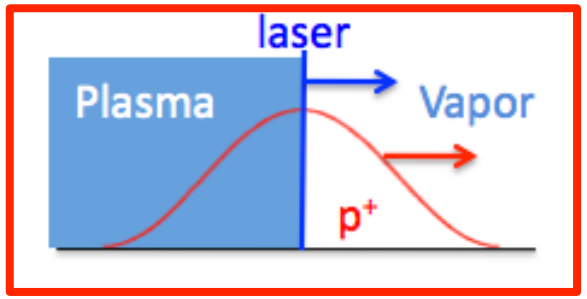




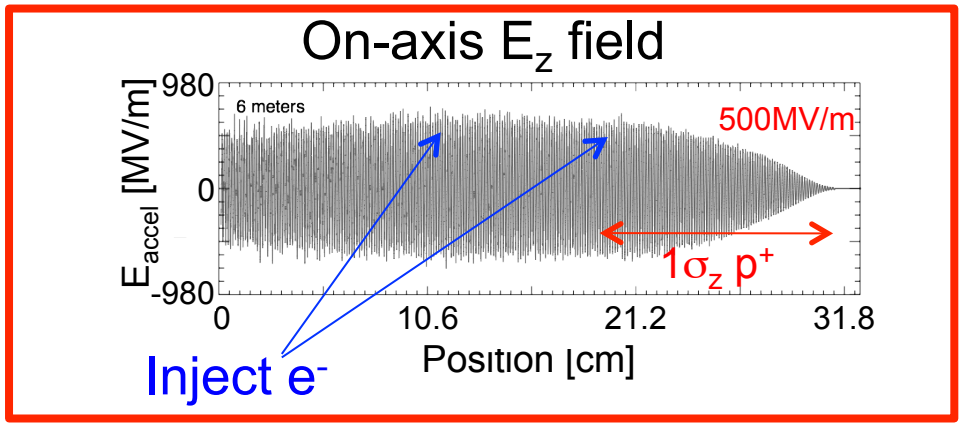
AWAKE Experiment @ CERN

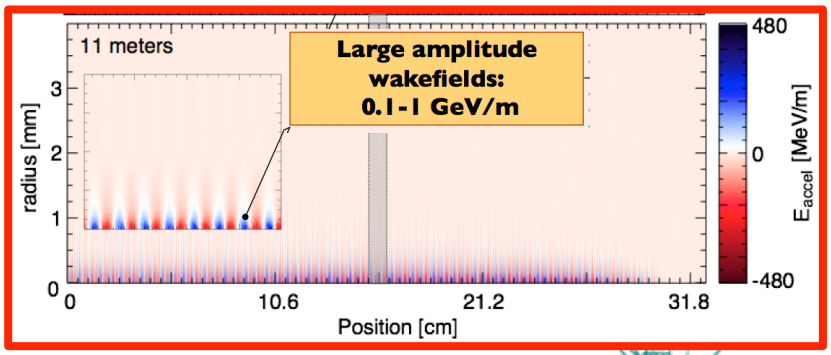






✧~GV/m accelerating field





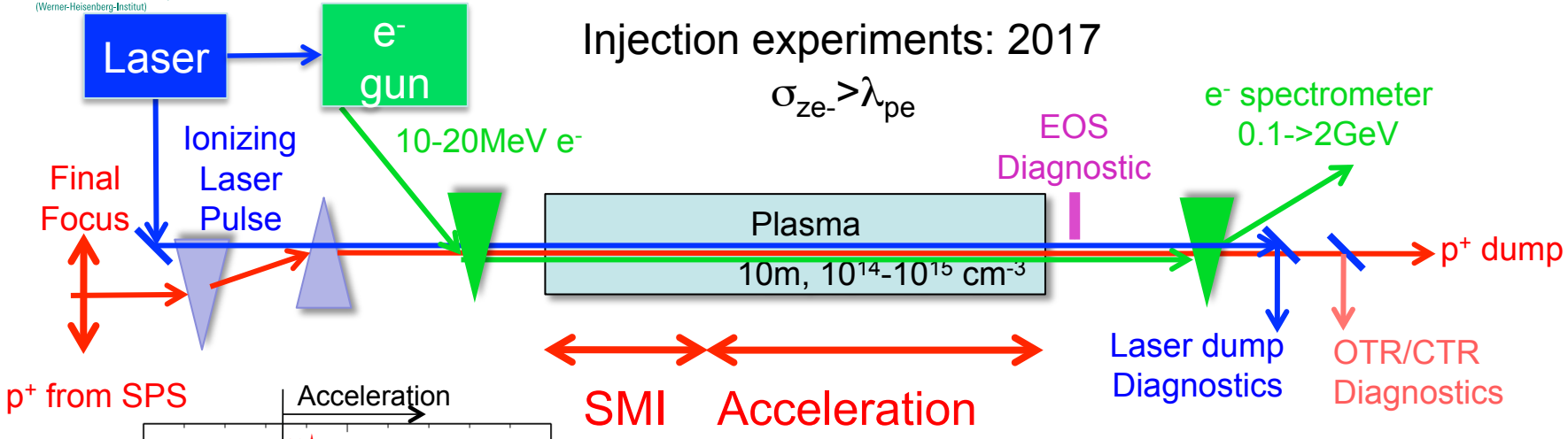
WAKEFIELDS SAMPLING / ACCELERATION

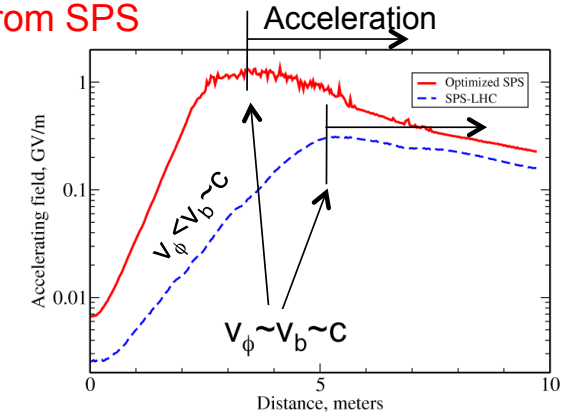
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

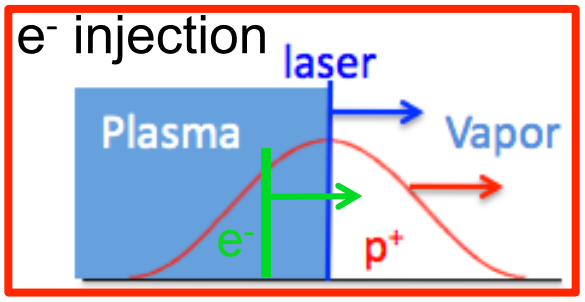
AWAKE

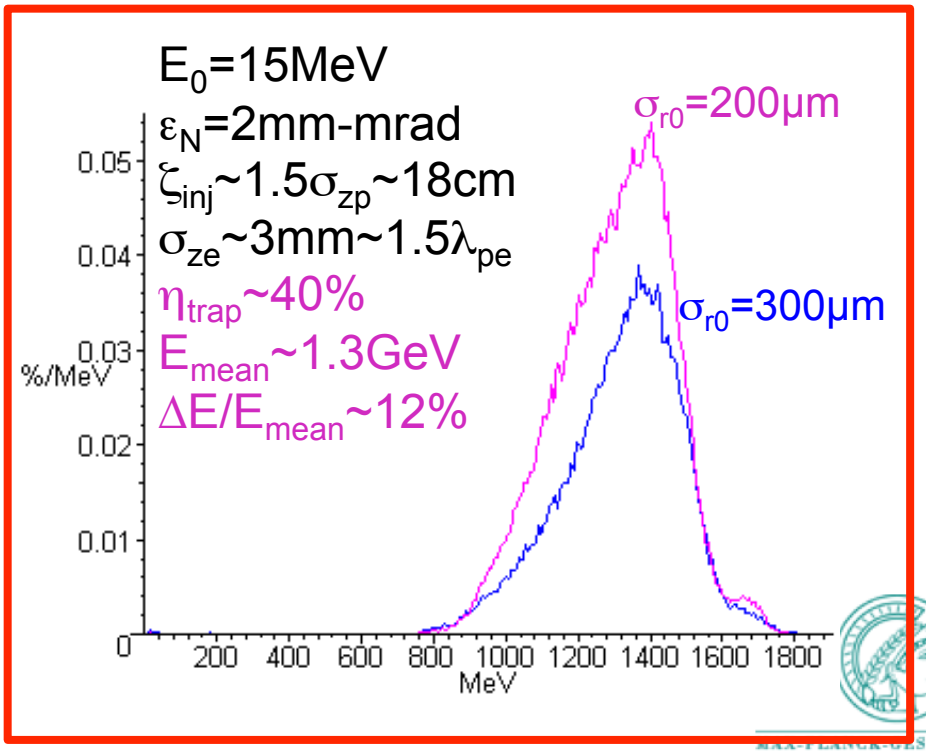
Injection experiments: 2017

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









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

WAKEFIELDS SAMPLING / ACCELERATION

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

AWAKE

Laser

e⁻ gun

O. Mete WEPWA059

eriments: 2017

e^- ->λ_{pe}

10-20Mev e^-

Ionizing Laser Pulse

Final Focus

EOS Diagnostic

e⁻ spectrometer 0.1->2Ge

L.C. Deacon WEPWA045

Plasma

10m, 10^{14}-10^{15} cm^{-3}

p⁺ dump

Laser dump

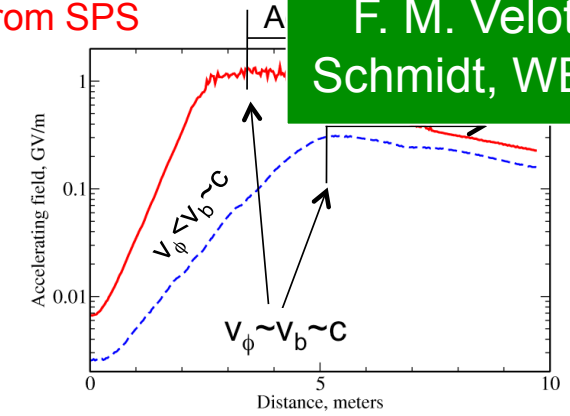
OTR/CTR Diagnostics

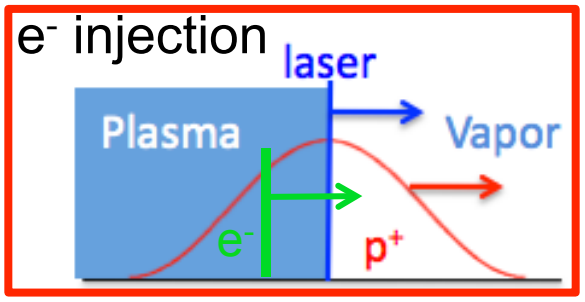
p⁺ from SPS

F. M. Velotti, J. S. Schmidt, WEPWA039

celeratio

U. Dorda WEPWA007





E_0=

ε_N=2mm-mrad

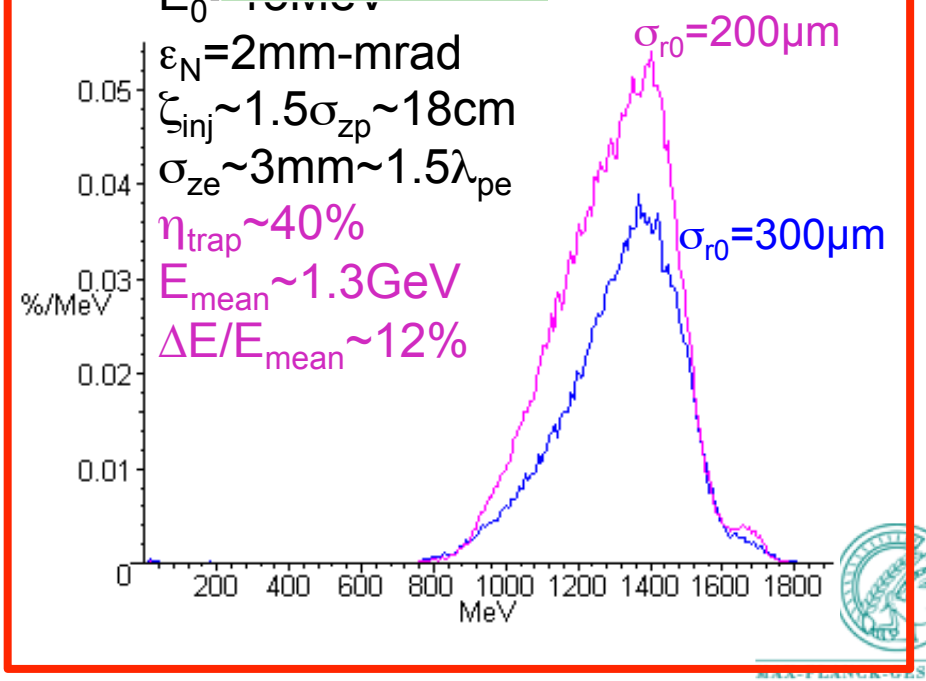
$\zeta_{inj} \sim 1.5\sigma_{zp} \sim 18$cm

$\sigma_{ze} \sim 3$mm$\sim 1.5\lambda_{pe}$

$\eta_{trap} \sim 40\%$

$E_{mean} \sim 1.3$GeV

$\Delta E/E_{mean} \sim 12\%$



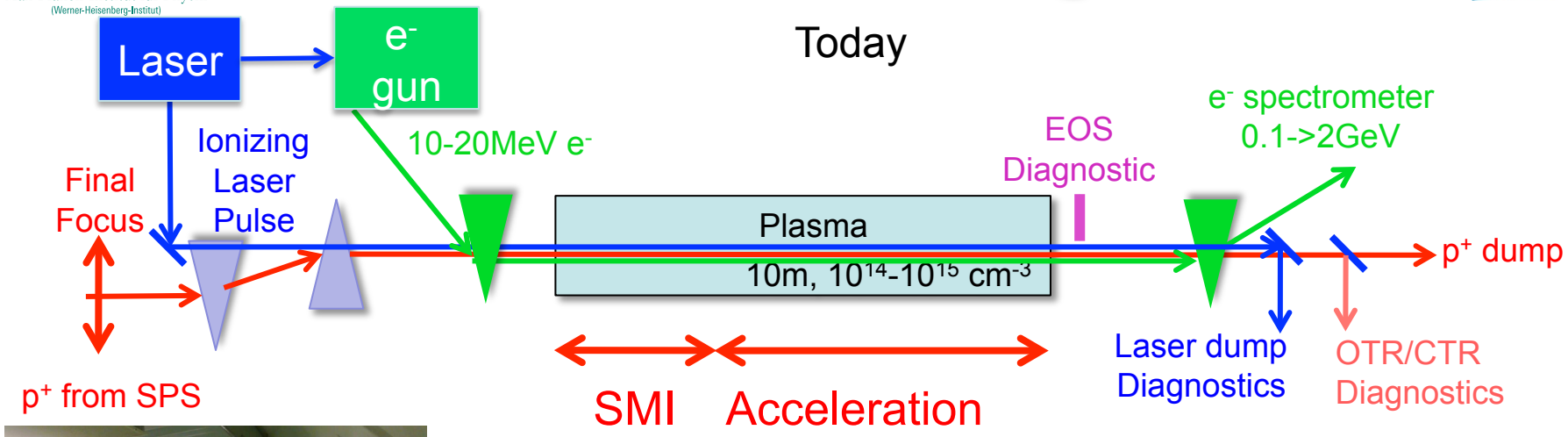
✧ Accelerate e^- to multi-GeV energies with ~GeV/m gradient

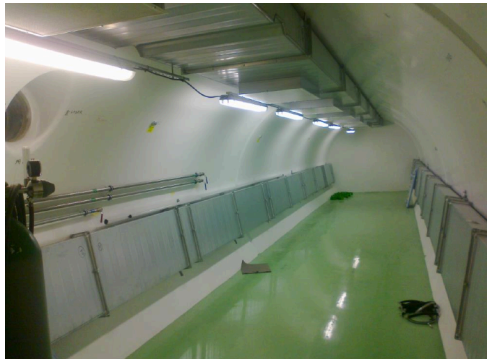
AWAKE EXPERIMENT @ CERN

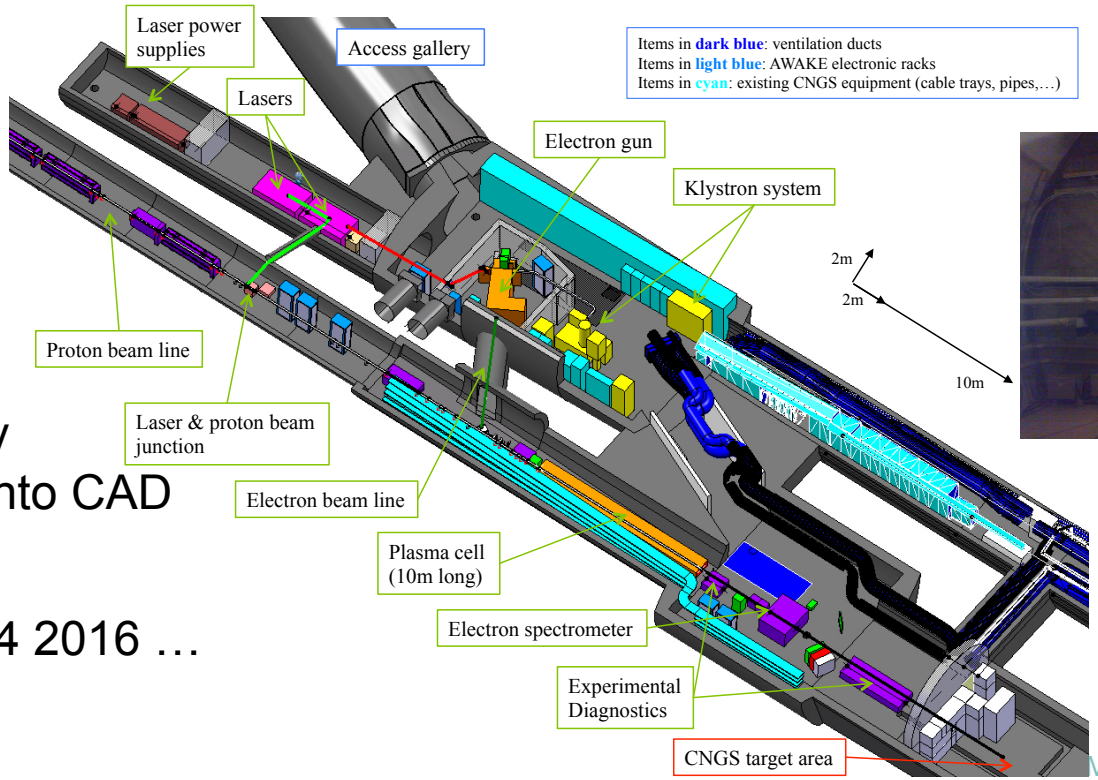
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

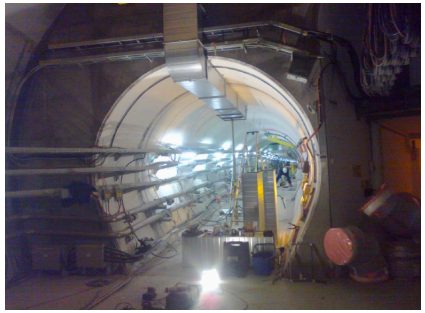
AWAKE

Today







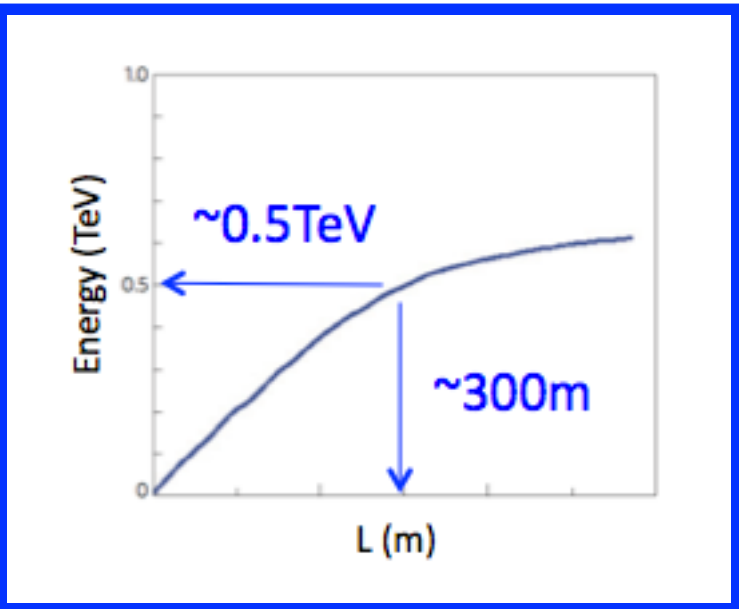


- CERN team already translated dreams into CAD and more
- SMI experiments Q4 2016 …

MAX-PLANCK-GESELLSCHAFT

SUMMARY

- p^+ bunches interesting because they carry large amounts of energy (10-100's kJ)



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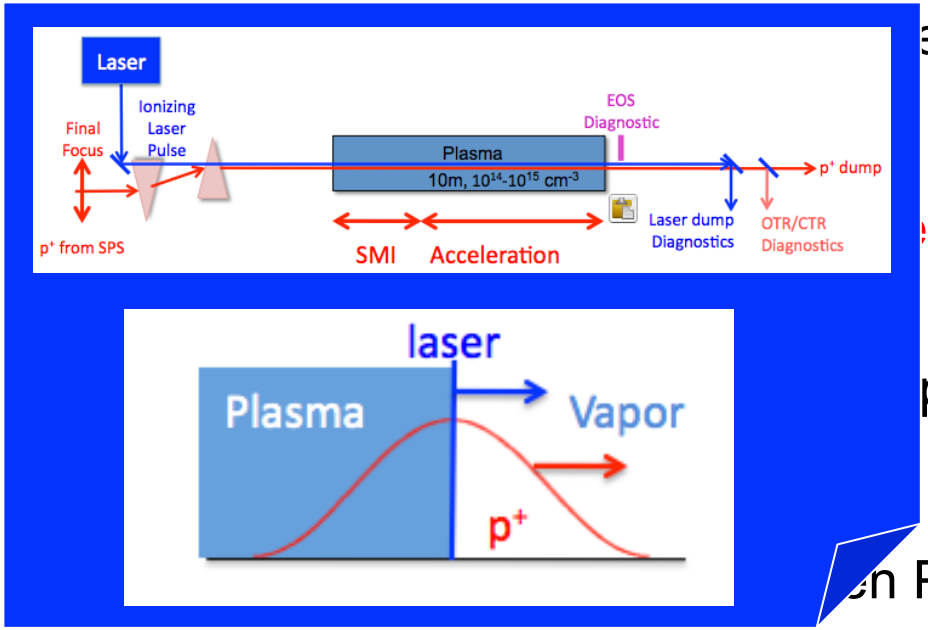
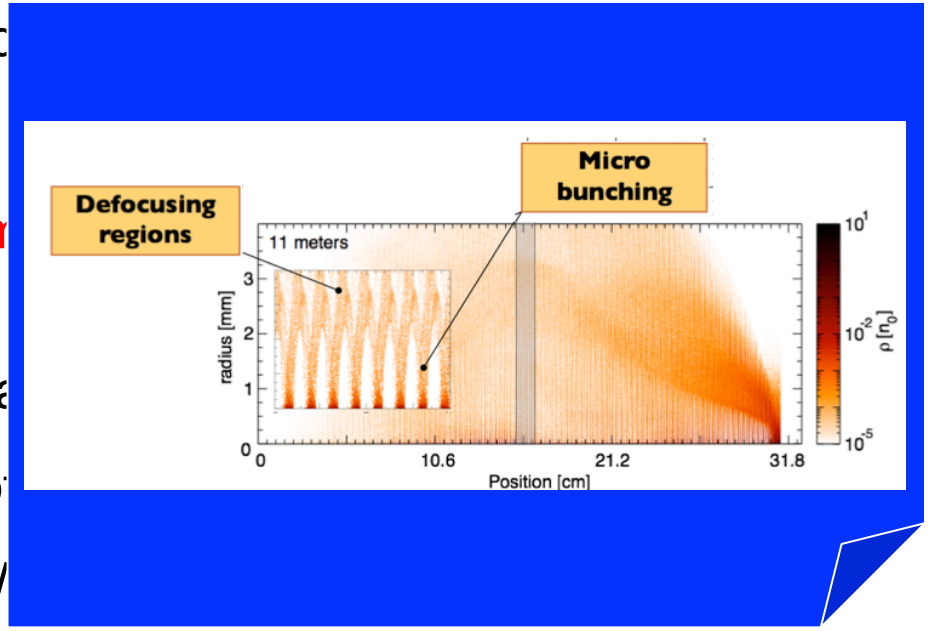
- Explore applications for a p^+-driven PWFA

SUMMARY

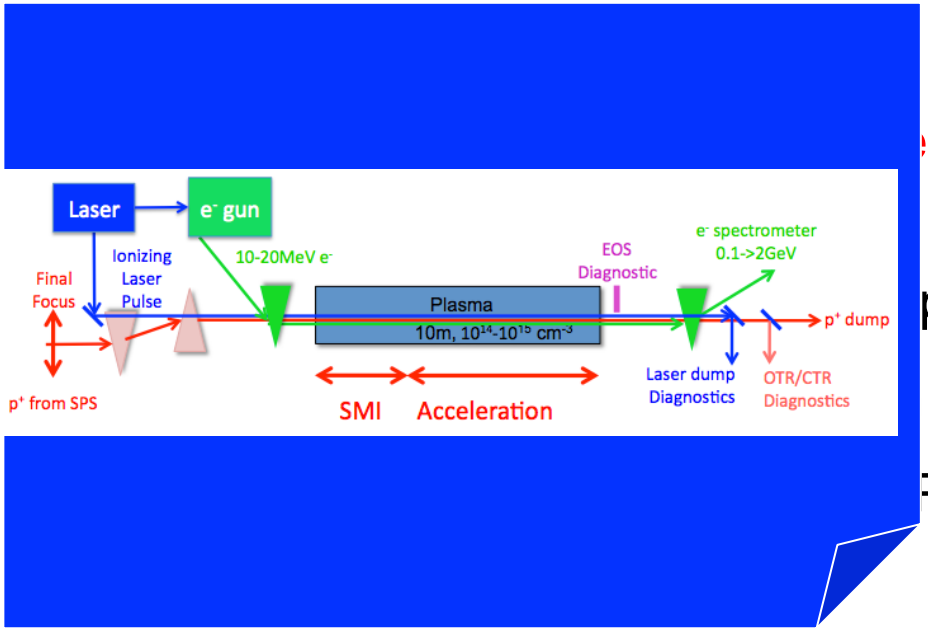
- p^+ bunches interesting because they carry large amounts of energy (10-100's kJ)
- 2016: study the physics of p^+ bunch SMI (radial modulation, seeding, …)

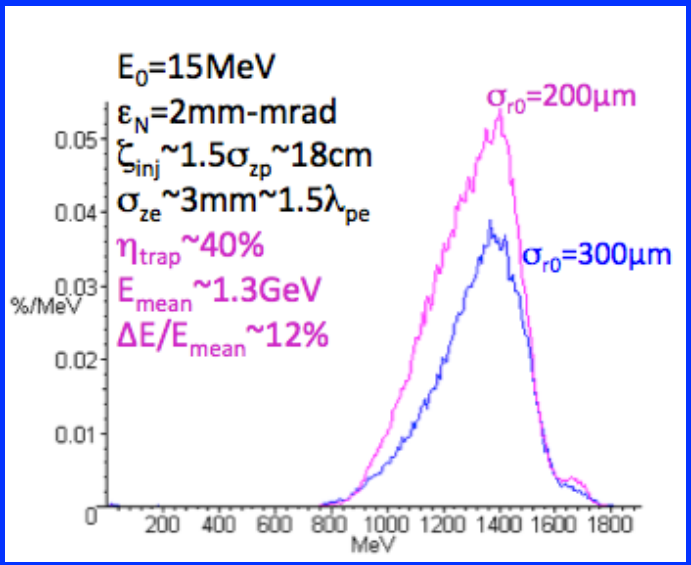




SUMMARY

- ✧p^+ bunches interesting because they carry large amounts of energy (10-100's kJ)
- ✧2016: study the physics of p^+ bunch SMI (radial modulation, seeding, …)
- ✧2017: probe the accelerating wakefields with externally injected e^-





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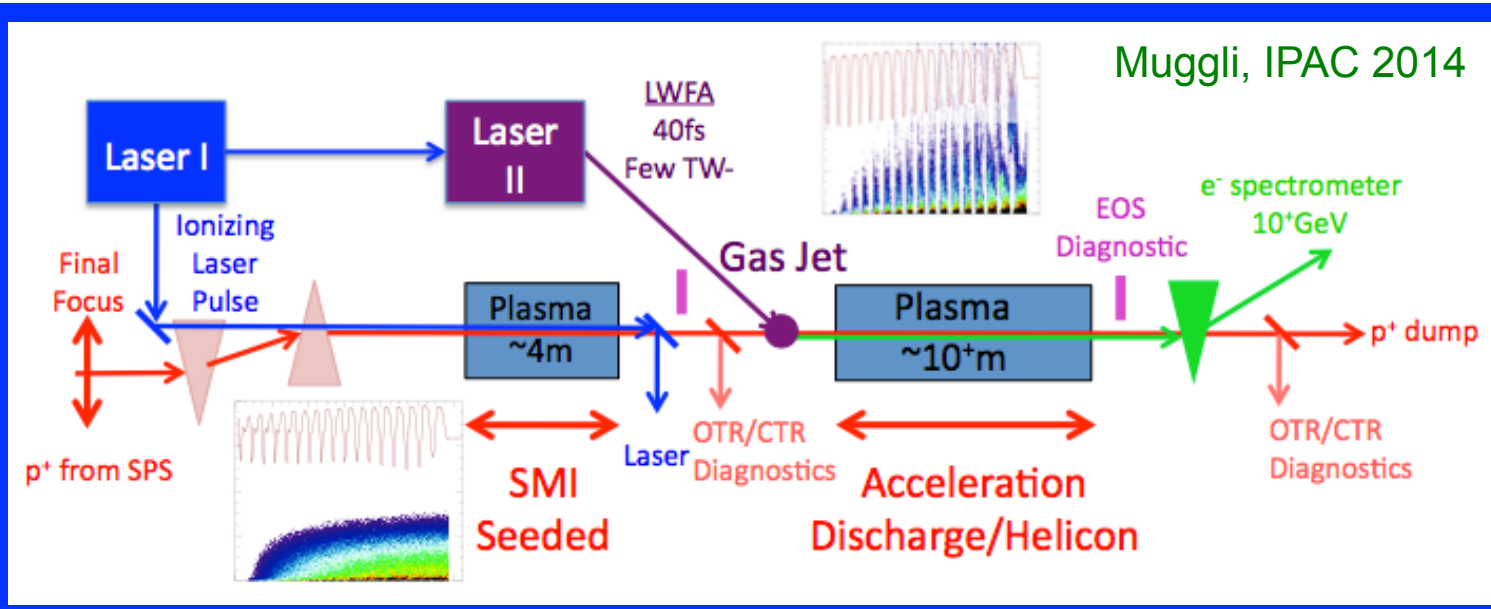

V. K. Berglyd Olsen
WEPWA026

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- 2016: study the physics of p^+ bunch SMI (radial modulation, seeding, …)
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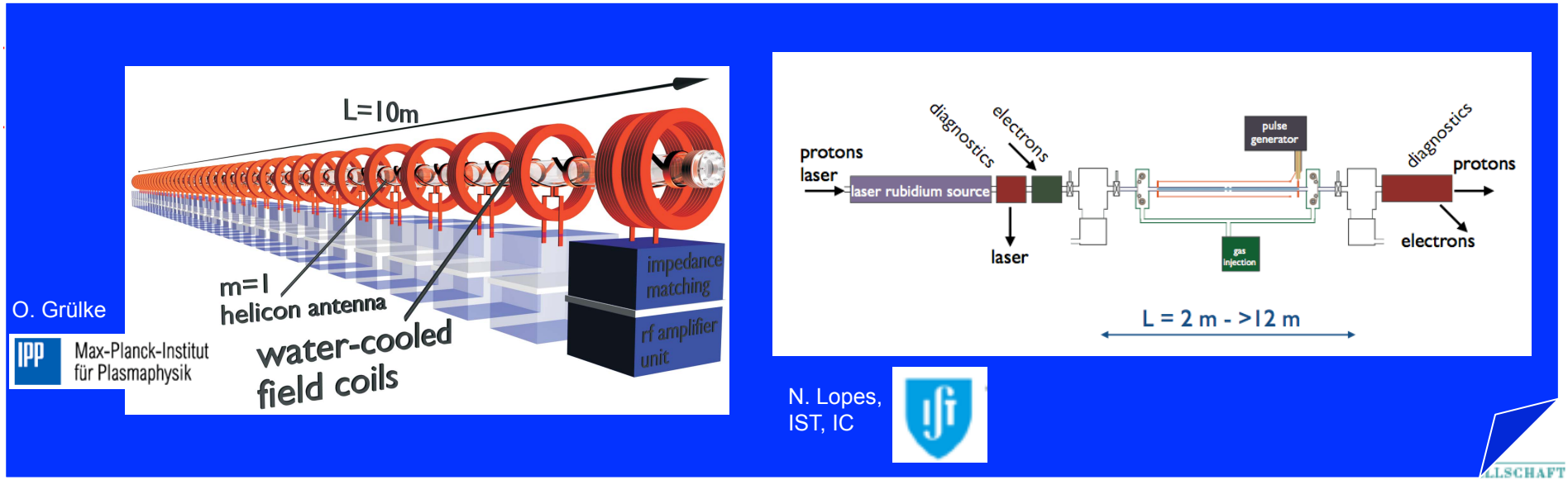
- 2017$^+$: study accelerator physics
- Set-up a comprehensive and long term p^+-driven plasma-based accelerator program at CERN
- Develop long, scalable and uniform plasma cells



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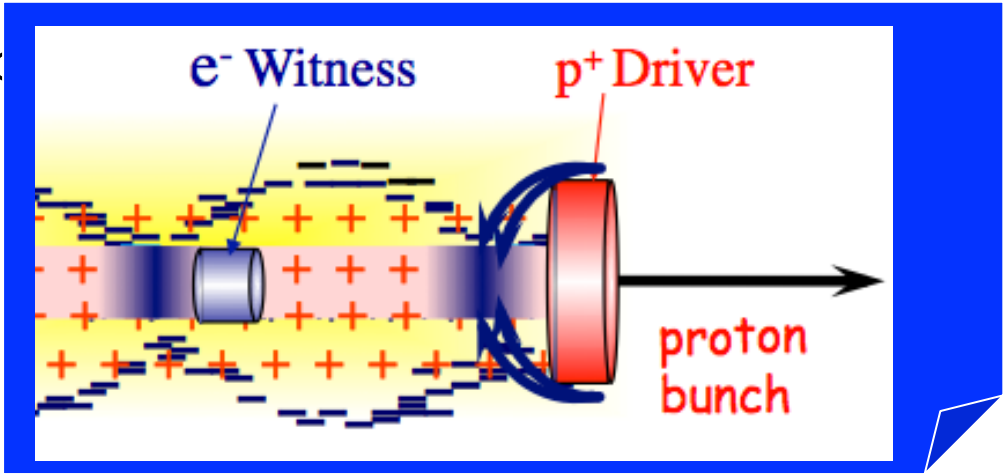
- Explore app



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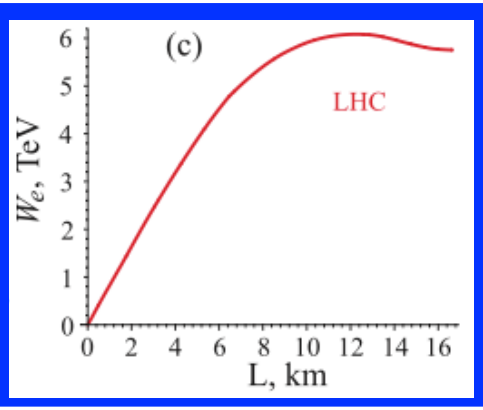
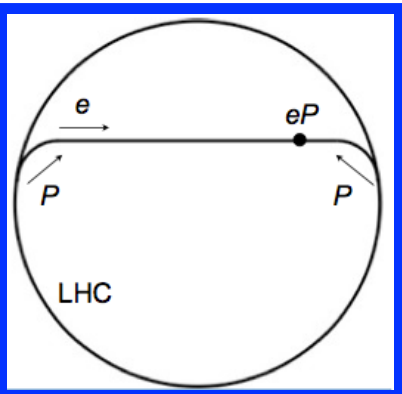




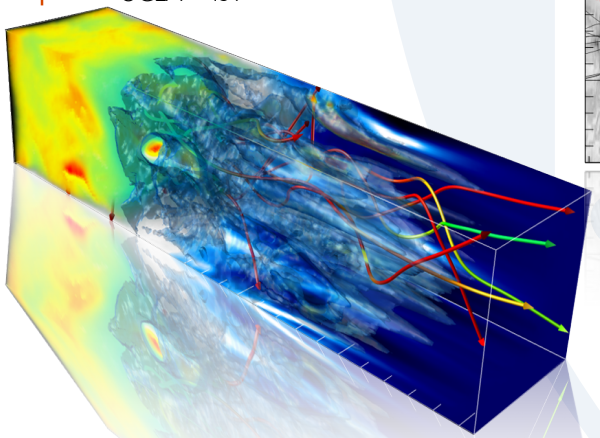
SMI-PWFA SIMULATIONS

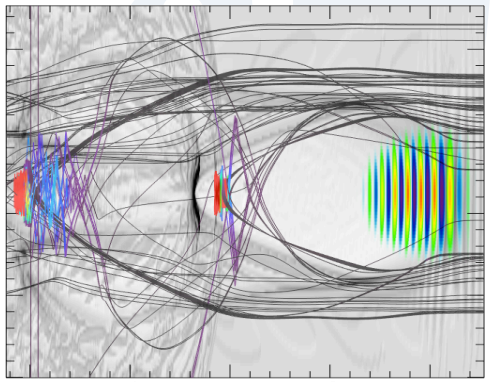
OSIRIS 2.0

osiris v2.0

osiris framework

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





New Features in v2.0

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

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

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

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

Benchmarking with:

- 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)

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

THANK YOU

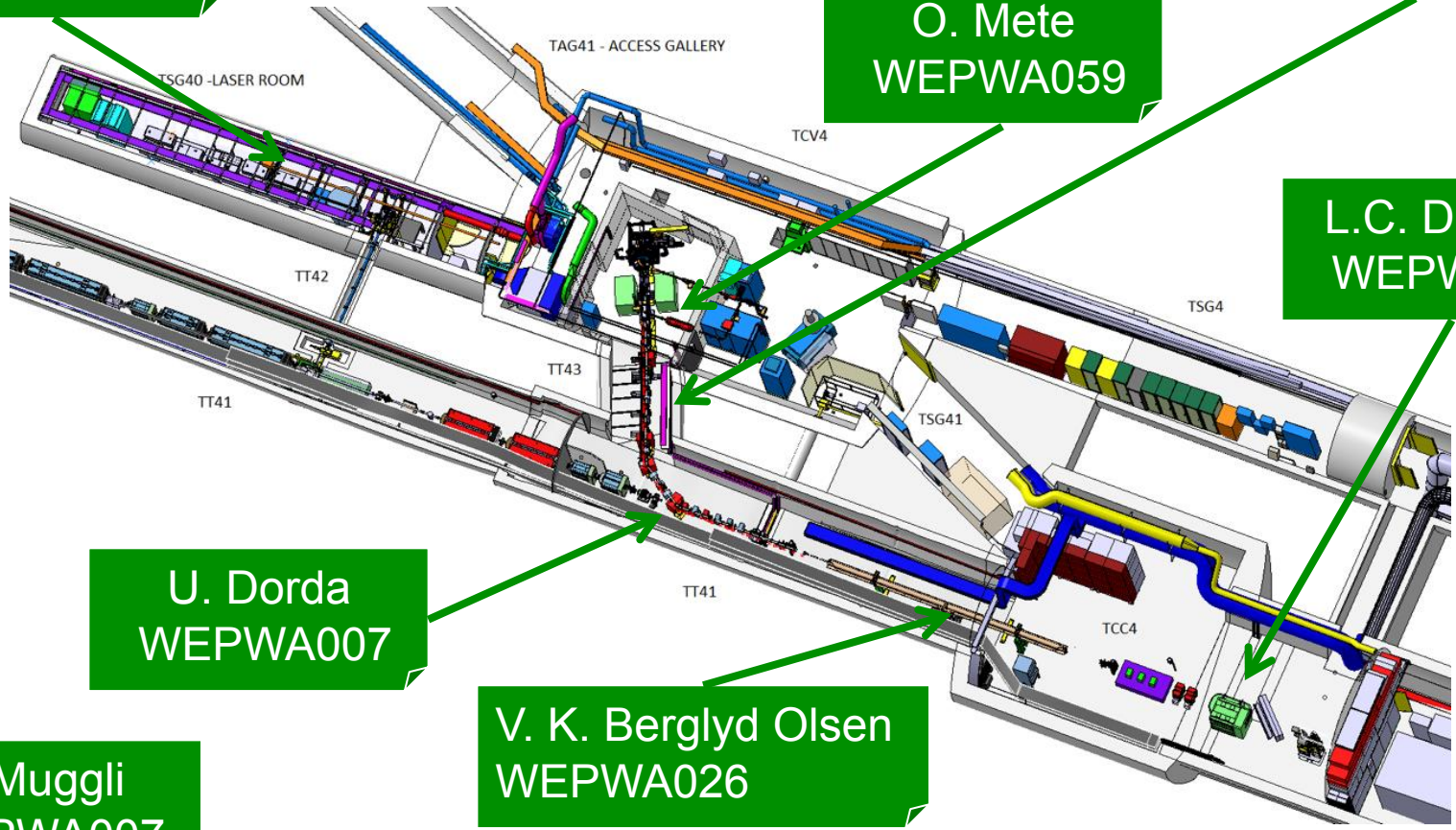
AWAKE

J. T. Moody
WEPWA047

F. M. Velotti, J. S. Schmidt, WEPWA039

O. Mete
WEPWA059

L.C. Deacon
WEPWA045



U. Dorda
WEPWA007

V. K. Berglyd Olsen
WEPWA026

P. Muggli
WEPWA007

P. Muggli
WEPWA008

THANK YOU

AWAKE

MAX-PLANCK-GESELLSCHAFT