Status and first results from AWAKE

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

AWAKE for 48 hours!

The first results!

(for the AWAKE Collaboration)

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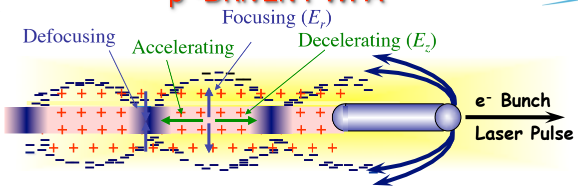
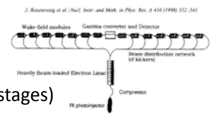
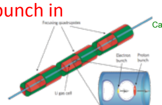
p+-DRiVEN PWFA



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



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

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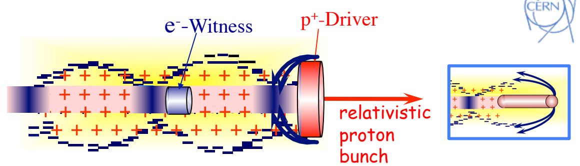
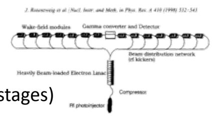
p+-DRiVEN PWFA



- ILC-CLIC, 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)



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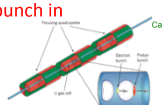
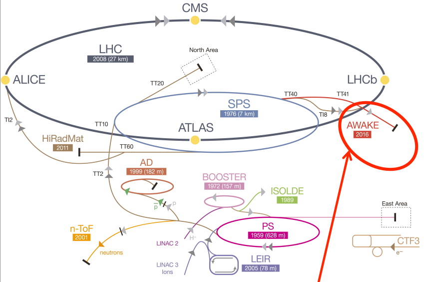


Caldwell, Nat. Phys. 5, 363, (2009)

PROTON BEAMS @ CERN

CERN's Accelerator Complex



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

AWAKE experimental area

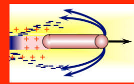
σ_z=12cm!!

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

PROTON BEAMS @ CERN

CERN's Accelerator Complex

Scaling



$\lambda_{pe}=2\pi c/\omega_{pe}=2\pi c/(n_e e^2/\varepsilon_0 m_e)^{1/2}$

$\sigma_z=12\text{cm}\sim\lambda_{pe} \rightarrow n_e\sim 8\times10^{10}\text{cm}^{-3}$

$\rightarrow E_{WB}=mc\omega_{pe}/e=2\pi mc^2/e\lambda_{pe}\sim 27\text{MV/m}$

PROTON BEAMS @ CERN

CERN's Accelerator Complex

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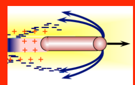

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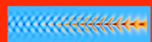


→Use self-modulation instability (SMI)

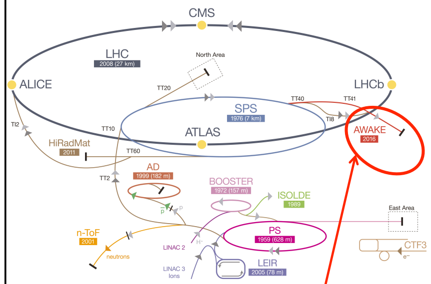
$\rightarrow\sigma_z\sim$12cm train with period ~1.2mm

$\rightarrow n_e\sim 7\times10^{14}\text{cm}^{-3}$, $(k_{pe}\sigma_r\sim 1)$, L_p=10m

$\rightarrow E_{WB}\sim$1GV/m, $f_{pe}\sim$237GHz

PROTON BEAMS @ CERN

CERN's Accelerator Complex



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σ_r^* (μm)	400	200	200
β^* (m)	1.6	5	5

$n_e\sim 7\times10^{14}\text{cm}^{-3}$ for $k_p\sigma_r\cong 1$

$\lambda_{pe}\sim 1.3\text{mm}\ll\sigma_z$

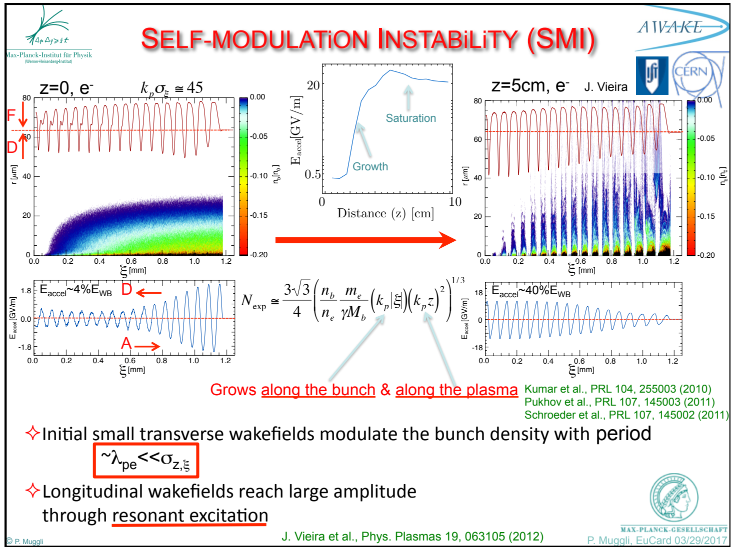
$f_{pe}\sim$240GHz

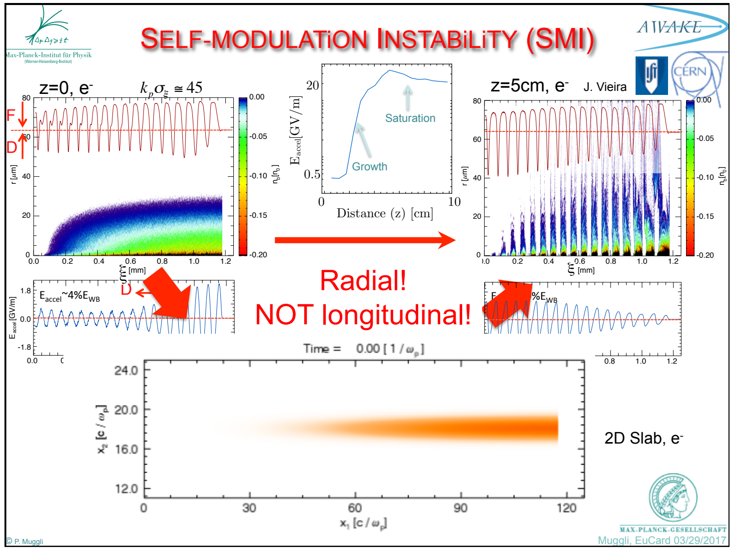
$L_p\sim 10\text{m}\sim 2\beta^*$

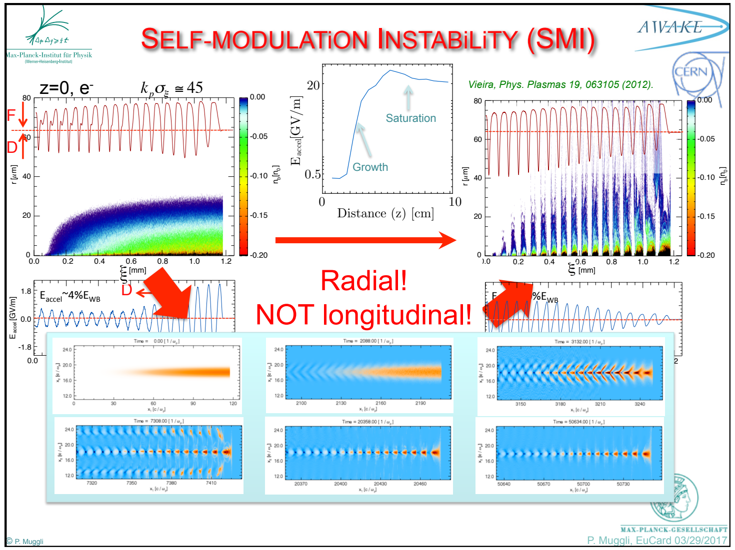
AWAKE experimental area

✧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


SELF-MODULATION INSTABILITY (SMI)
AWAKE
CERN
z=0, e-
$k_p\sigma_\xi \cong 45$
z=5cm, e-
J. Vieira
Saturation
Growth
Distance (z) [cm]
E_{accel}~4%E_{WB}
E_{accel}~40%E_{WB}
$N_{exp} \cong \frac{3\sqrt{3}}{4}\left(\frac{n_b}{n_e}\frac{m_e}{\gamma M_b}(k_p|\xi|)(k_p z)^2\right)^{1/3}$
Grows along the bunch & along the plasma
Kumar et al., PRL 104, 255003 (2010)
Pukhov et al., PRL 107, 145003 (2011)
Schroeder et al., PRL 107, 145002 (2011)
✧Initial small transverse wakefields modulate the bunch density with period
$\sim\lambda_{pe} << \sigma_{z,\xi}$
✧Longitudinal wakefields reach large amplitude through resonant excitation
J. Vieira et al., Phys. Plasmas 19, 063105 (2012)
P. Muggli, EuCard 03/29/2017


SELF-MODULATION INSTABILITY (SMI)
AWAKE
z=0, e-
$k_p\sigma_\xi \cong 45$
z=5cm, e-
J. Vieira
Saturation
Growth
Distance (z) [cm]
Radial!
NOT longitudinal!
Time = 0.00 [1/ω_p]
2D Slab, e-
P. Muggli, EuCard 03/29/2017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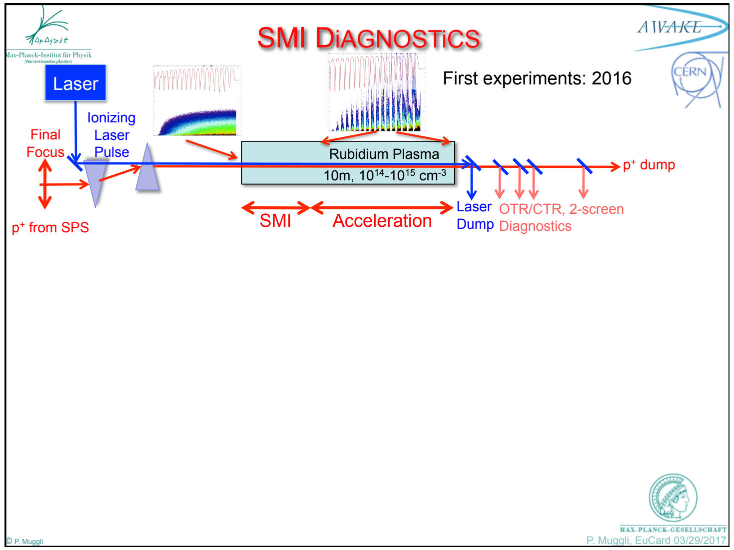
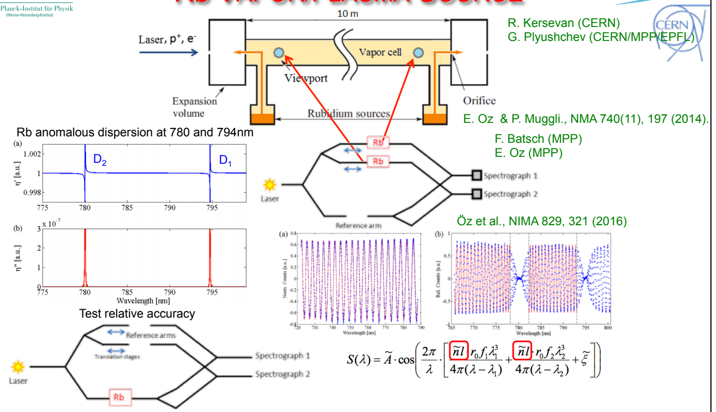
AWAKE
z=0, e-
$k_p\sigma_\xi \cong 45$
Vieira, Phys. Plasmas 19, 063105 (2012).
Saturation
Growth
Distance (z) [cm]
Radial!
NOT longitudinal!
P. Muggli, EuCard 03/29/2017


SMI DIAGNOSTICS
AWAKE
First experiments: 2016
Laser
Ionizing Laser Pulse
Final Focus
Rubidium Plasma
10m, 10^{14}-10^{15} cm^{-3}
p+ dump
p+ from SPS
SMI
Acceleration
Laser Dump
OTR/CTR, 2-screen Diagnostics
P. Muggli, EuCard 03/29/2017

Rb VAPOR/PLASMA SOURCE



R. Kersevan (CERN)
G. Plyushchev (CERN/MPP/EPFL)
E. Oz & P. Muggli., NMA 740(11), 197 (2014).
F. Batsch (MPP)
E. Oz (MPP)
Öz et al., NIMA 829, 321 (2016)

- ✧Requirements: $10^{14}<n_{Rb,e}<10^{15}cm^{-3}$, $\Delta n_{Rb,e}/n_{Rb,e}<0.2\%$, few cm $n_{Rb,e}$ ramp
- ✧Impose temperature $\Delta T<0.3K$ @500K ($\Delta T/T=\Delta n_{Rb}/n_{Rb}<0.2\%$) + free expansion at ends
- ✧Anomalous dispersion for n_{Rb} measurement: <0.3% accuracy!
- ✧Meets all specs …

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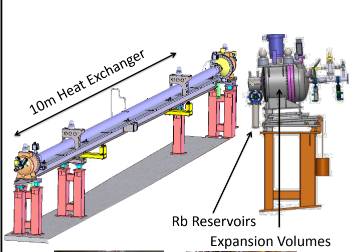
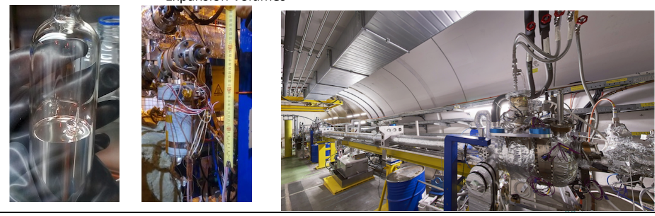
P. Muggli, EuCard 03/29/2017

Rb VAPOR SOURCE (heat exchanger)

Development of the ends | Installed in AWAKE!





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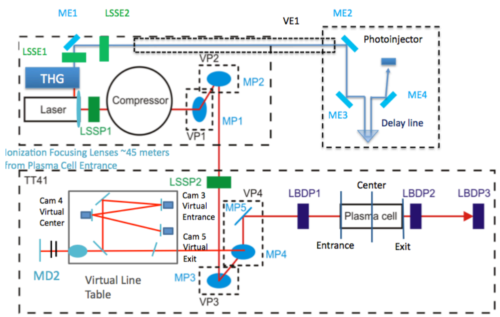
LASER & PLASMA



J. Moody, M. Huether, MPP, V. Fedosseev, F. Friebel, CERN

- ✧Fiber/Ti-Sapphire laser: ~100fs, E_{max}=450mJ
- ✧Rb: ϕ_{IP}=4.177eV, I_{app}~1.7×10^{12}Wcm^{-2},
- ✧r_0~1mm, Z_R~5m, I_{max}>10×10^{12}Wcm^{-2}
- ✧Field ionization => $n_e=n_{Rb}$, uniformity and ramps
- ✧Virtual plasma for alignment

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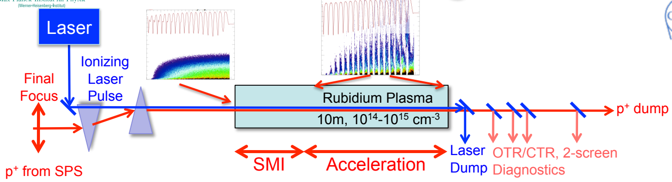
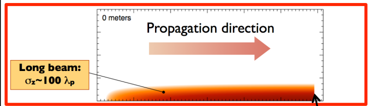
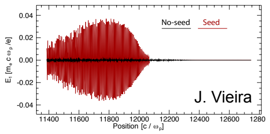
AWAKE EXPERiMENT @ CERN







✧No seed no SMI (over 10m)

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

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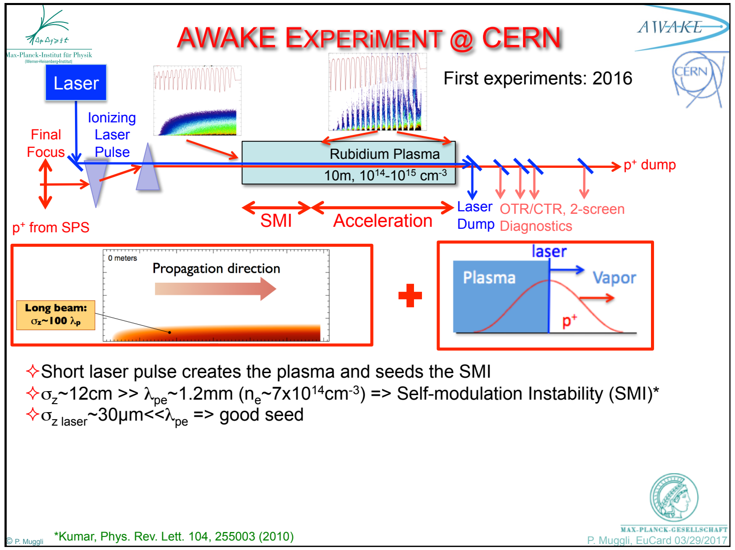
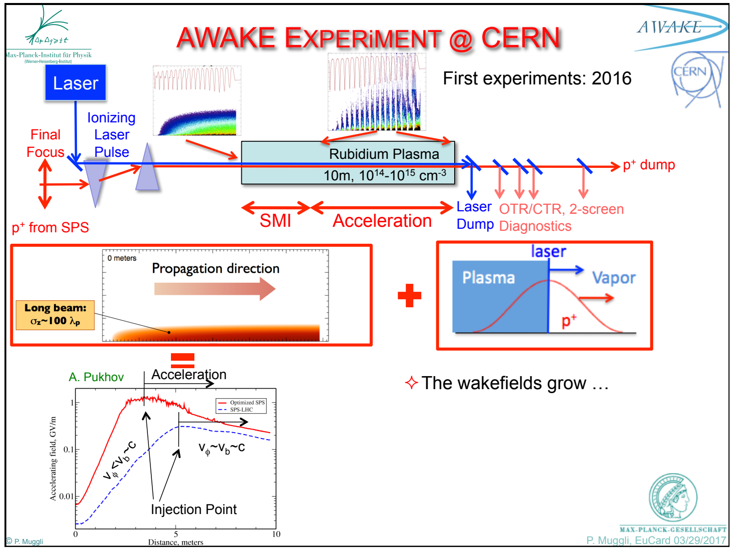

AWAKE EXPERIMENT @ CERN
AWAKE
CERN
Laser
First experiments: 2016
Ionizing
Laser
Pulse
Final
Focus
Rubidium Plasma
10m, 10^14-10^15 cm^-3
p+ dump
SMI
Acceleration
Laser
Dump
OTR/CTR, 2-screen
Diagnostics
p+ from SPS
Propagation direction
Long beam:
σz~100 λp
laser
Plasma
Vapor
p+
✧Short laser pulse creates the plasma and seeds the SMI
✧σz~12cm >> λpe~1.2mm (ne~7x10^14cm^-3) => Self-modulation Instability (SMI)*
✧σz laser~30µm<<λpe => good seed
*Kumar, Phys. Rev. Lett. 104, 255003 (2010)
MAX-PLANCK-GESELLSCHAFT
P. Muggli, EuCard 03/29/2017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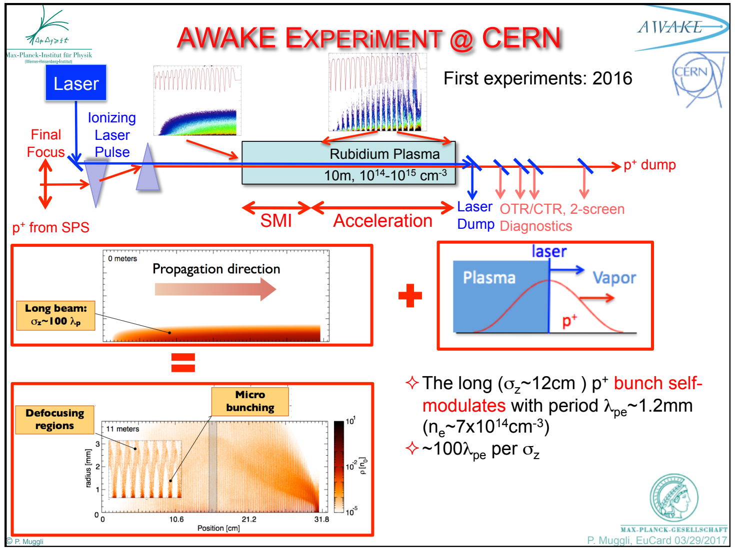
p+ from SPS
Propagation direction
Long beam:
σz~100 λp
laser
Plasma
Vapor
p+
A. Pukhov
Acceleration
vφ<vb~c
vφ~vb~c
Injection Point
Distance, meters
✧The wakefields grow …
MAX-PLANCK-GESELLSCHAFT
P. Muggli, EuCard 03/29/2017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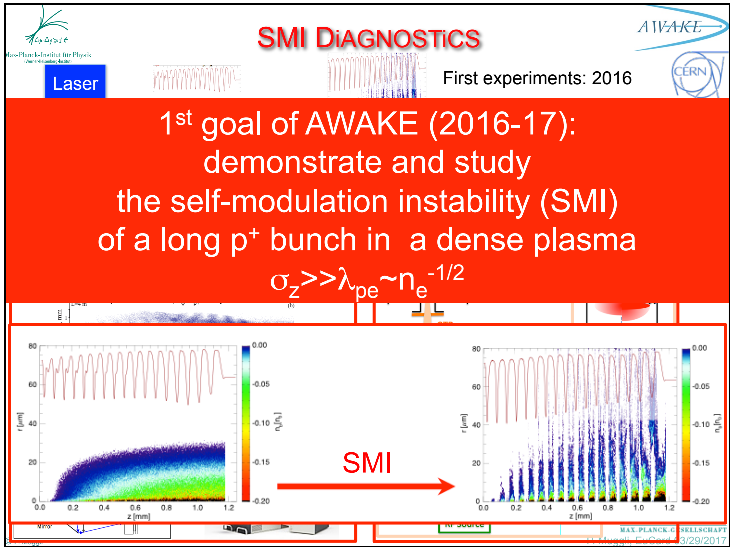
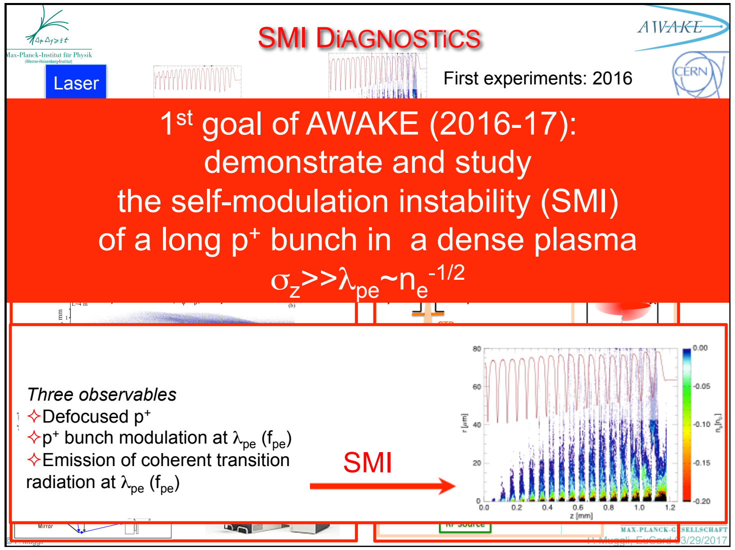
Laser
Dump
OTR/CTR, 2-screen
Diagnostics
p+ from SPS
Propagation direction
Long beam:
σz~100 λp
laser
Plasma
Vapor
p+
Defocusing
regions
Micro
bunching
Position [cm]
✧The long (σz~12cm) p+ bunch self-modulates with period λpe~1.2mm (ne~7x10^14cm^-3)
✧~100λpe per σz
MAX-PLANCK-GESELLSCHAFT
P. Muggli, EuCard 03/29/2017


SMI DIAGNOSTICS
AWAKE
CERN
Laser
First experiments: 2016
1st goal of AWAKE (2016-17):
demonstrate and study
the self-modulation instability (SMI)
of a long p+ bunch in a dense plasma
σz>>λpe~ne^-1/2
SMI
z [mm]
MAX-PLANCK-GESELLSCHAFT


SMI DiAGNOSTiCS
AWAKE
First experiments: 2016
Laser
1st goal of AWAKE (2016-17):
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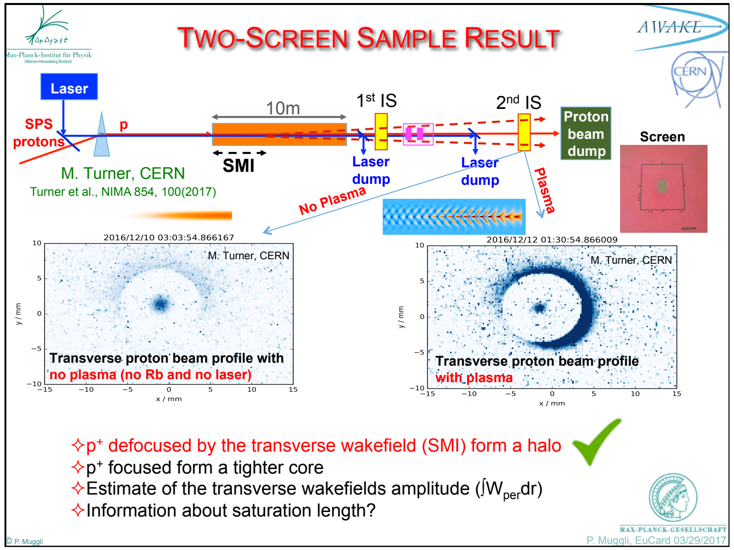
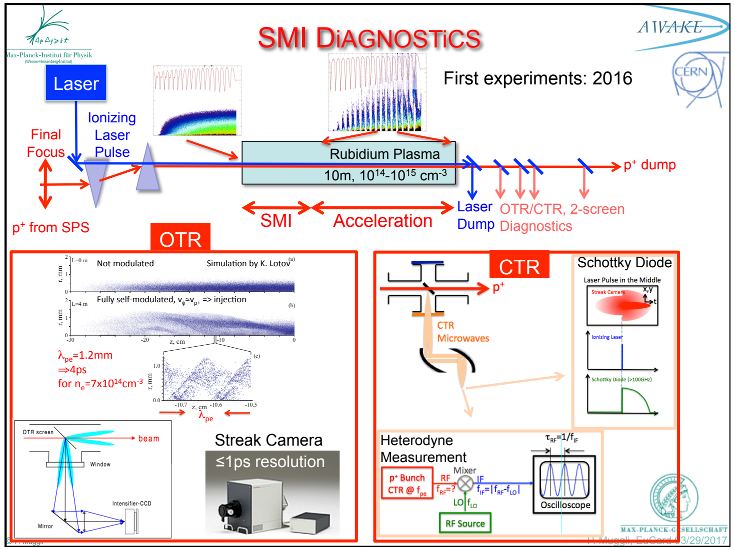
the self-modulation instability (SMI)
of a long p+ bunch in a dense plasma
σz>>λpe~ne-1/2
Three observables
✧Defocused p+
✧p+ bunch modulation at λpe (fpe)
✧Emission of coherent transition radiation at λpe (fpe)
SMI
P. Muggli, EuCard 03/29/2017


TWO-SCREEN SAMPLE RESULT
AWAKE
Laser
SPS protons
p
10m
1st IS
2nd IS
Proton beam dump
Screen
SMI
Laser dump
Laser dump
M. Turner, CERN
Turner et al., NIMA 854, 100(2017)
No Plasma
Plasma
2016/12/10 03:03:54.866167
2016/12/12 01:30:54.866009
M. Turner, CERN
M. Turner, CERN
Transverse proton beam profile with no plasma (no Rb and no laser)
Transverse proton beam profile with plasma
✧p+ defocused by the transverse wakefield (SMI) form a halo
✧p+ focused form a tighter core
✧Estimate of the transverse wakefields amplitude (∫Wperdr)
✧Information about saturation length?
P. Muggli, EuCard 03/29/2017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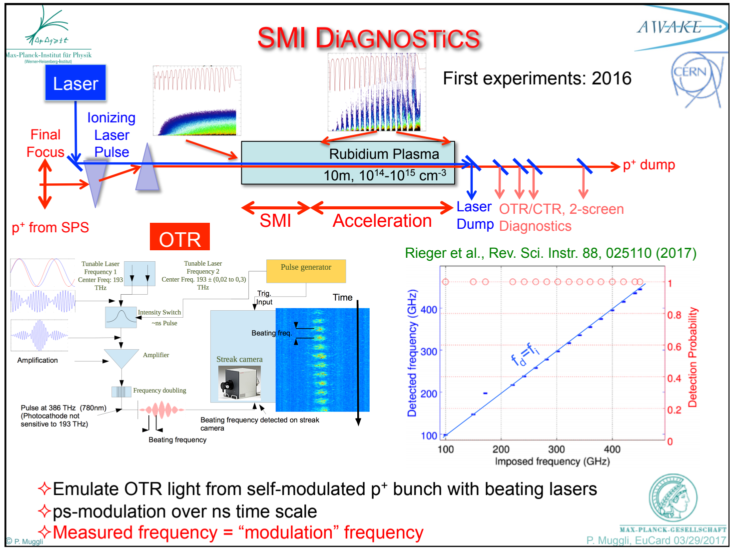
Final Focus
Rubidium Plasma
10m, 1014-1015 cm-3
p+ dump
p+ from SPS
SMI
Acceleration
Laser Dump
OTR/CTR, 2-screen Diagnostics
OTR
CTR
Not modulated
Simulation by K. Lotov
Fully self-modulated, vb=vph => injection
λpe=1.2mm
⇒4ps
for ne=7x1014cm-3
Schottky Diode
Streak Camera
≤1ps resolution
Heterodyne Measurement
Mixer
Oscilloscope
RF Source
CTR Microwaves
P. Muggli, EuCard 03/29/2017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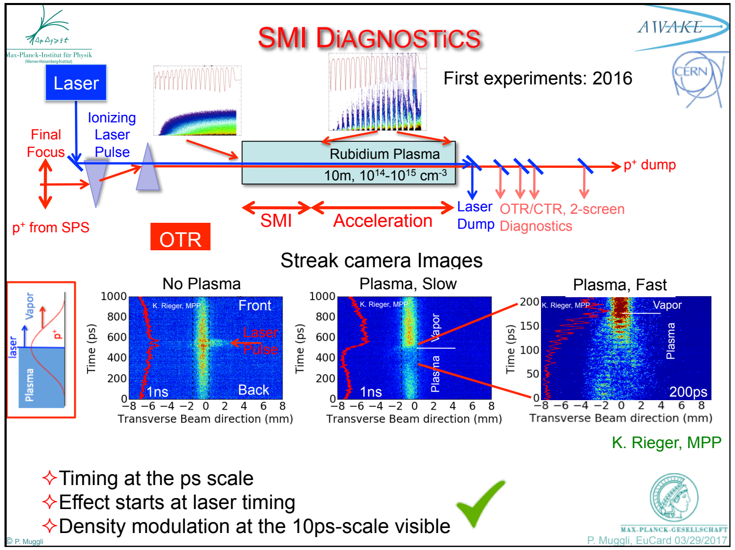
SMI
Acceleration
Laser Dump
OTR/CTR, 2-screen Diagnostics
OTR
Rieger et al., Rev. Sci. Instr. 88, 025110 (2017)
Pulse generator
Streak camera
Time
Amplification
Detected frequency (GHz)
Imposed frequency (GHz)
Detection Probability
fd=fi
✧Emulate OTR light from self-modulated p+ bunch with beating lasers
✧ps-modulation over ns time scale
✧Measured frequency = "modulation" frequency
P. Muggli, EuCard 03/29/2017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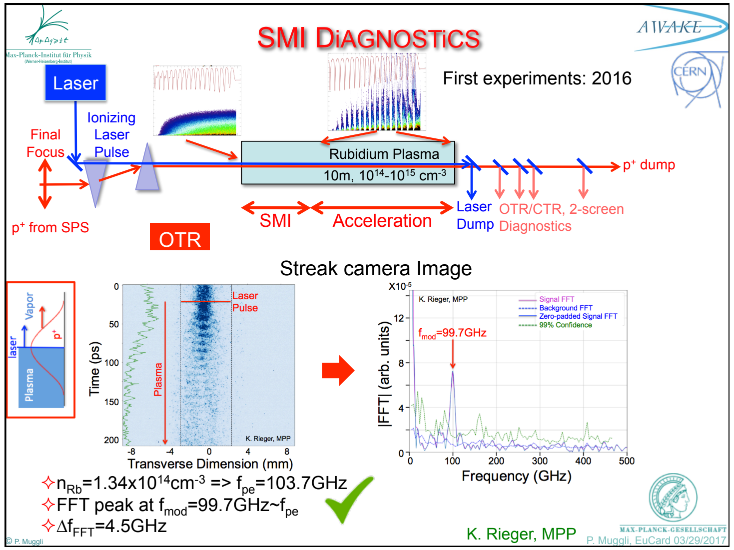
p+ from SPS
Rubidium Plasma
10m, 10^14-10^15 cm-3
p+ dump
SMI
Acceleration
Laser Dump
OTR/CTR, 2-screen Diagnostics
OTR
Streak camera Images
No Plasma
Plasma, Slow
Plasma, Fast
Time (ps)
Transverse Beam direction (mm)
Front
Back
Vapor
Plasma
1ns
200ps
K. Rieger, MPP
✧Timing at the ps scale
✧Effect starts at laser timing
✧Density modulation at the 10ps-scale visible
P. Muggli, EuCard 03/29/2017


SMI DiAGNOSTiCS
AWAKE
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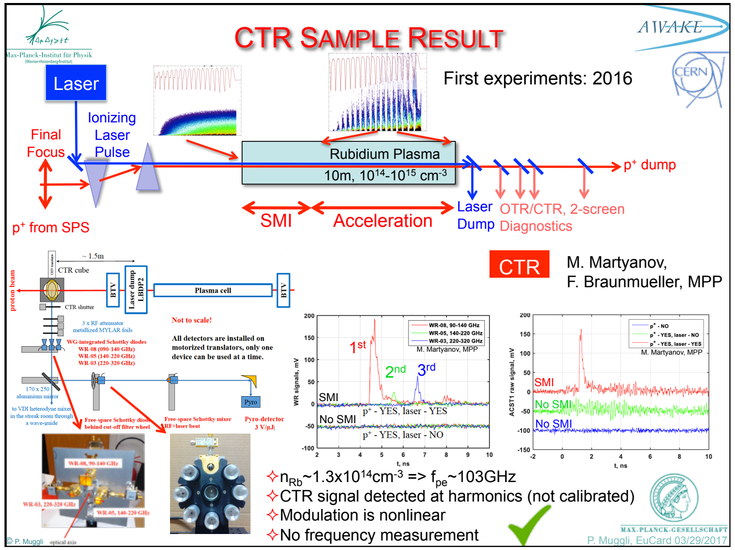
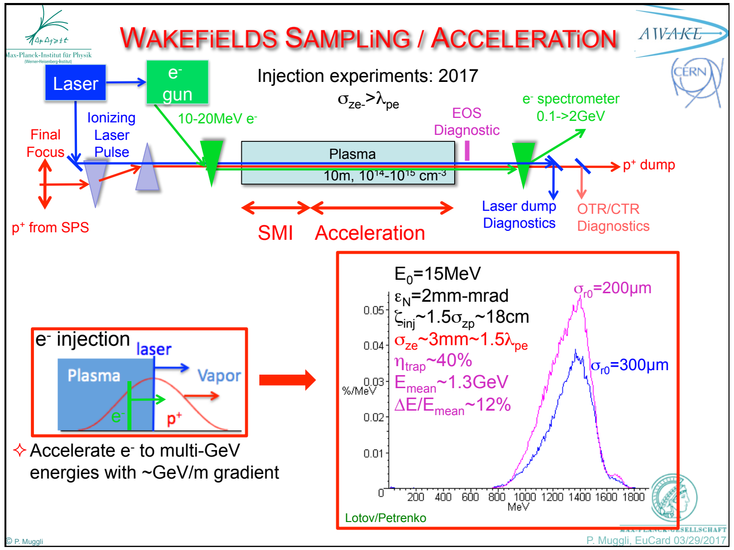
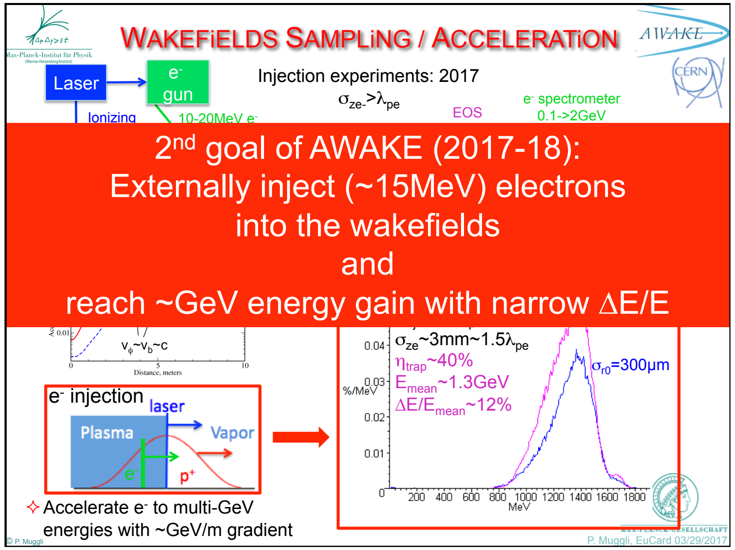
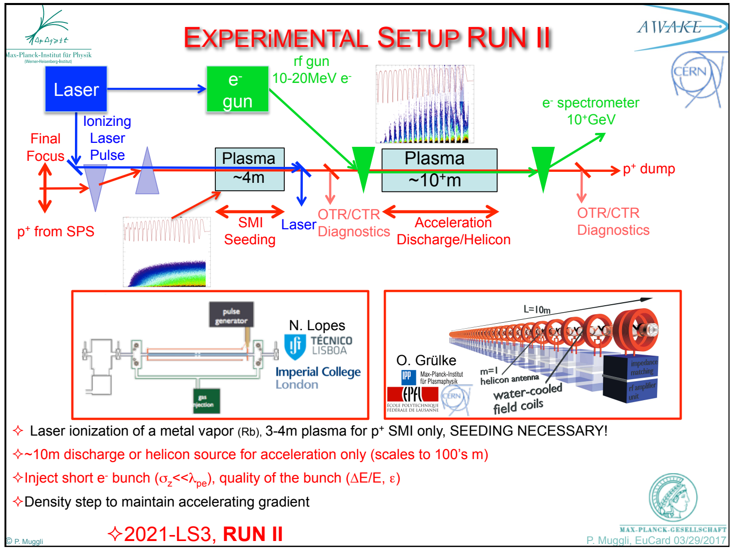
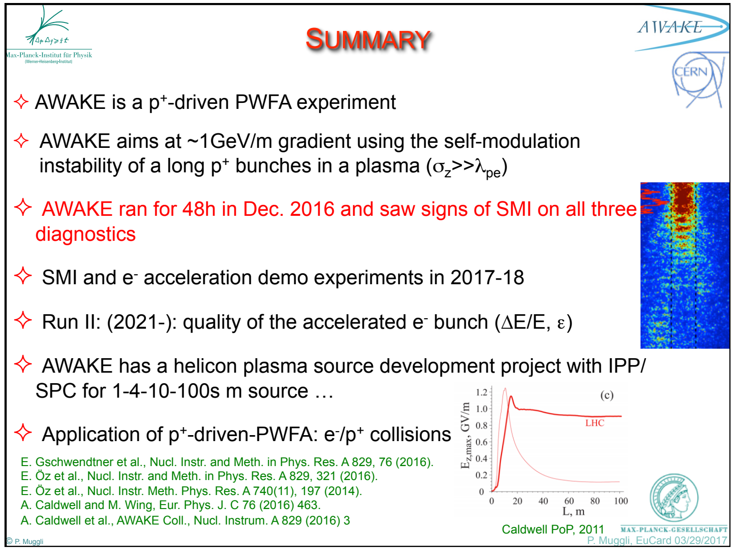
Laser
Ionizing Laser Pulse
Final Focus
p+ from SPS
Rubidium Plasma
10m, 10^14-10^15 cm-3
p+ dump
SMI
Acceleration
Laser Dump
OTR/CTR, 2-screen Diagnostics
OTR
Streak camera Image
Time (ps)
Transverse Dimension (mm)
Laser Pulse
Plasma
|FFT| (arb. units)
Frequency (GHz)
f_mod=99.7GHz
✧n_Rb=1.34x10^14cm-3 => f_pe=103.7GHz
✧FFT peak at f_mod=99.7GHz~f_pe
✧Δf_FFT=4.5GHz
K. Rieger, MPP
P. Muggli, EuCard 03/29/2017


CTR SAMPLE RESULT
AWAKE
First experiments: 2016
Laser
Ionizing Laser Pulse
Final Focus
p+ from SPS
Rubidium Plasma
10m, 10^14-10^15 cm-3
p+ dump
SMI
Acceleration
Laser Dump
OTR/CTR, 2-screen Diagnostics
CTR
M. Martyanov, F. Braunmueller, MPP
1st
2nd
3rd
SMI
No SMI
✧n_Rb~1.3x10^14cm-3 => f_pe~103GHz
✧CTR signal detected at harmonics (not calibrated)
✧Modulation is nonlinear
✧No frequency measurement
P. Muggli, EuCard 03/29/2017

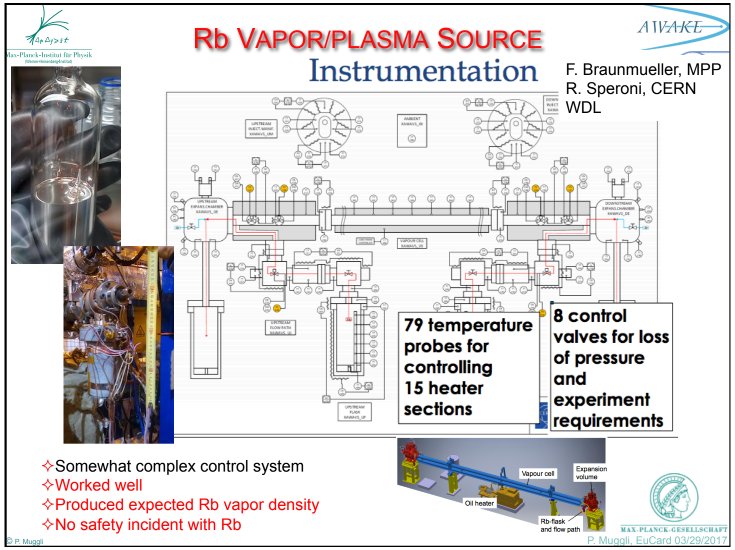

WAKEFiELDS SAMPLiNG / ACCELERATiON
AWAKE
Injection experiments: 2017
Laser
e- gun
10-20MeV e-
σ_ze>λ_pe
EOS Diagnostic
e- spectrometer 0.1->2GeV
Ionizing Laser Pulse
Final Focus
p+ from SPS
Plasma
10m, 10^14-10^15 cm-3
p+ dump
SMI
Acceleration
Laser dump Diagnostics
OTR/CTR Diagnostics
e- injection
laser
Plasma
Vapor
✧Accelerate e- to multi-GeV energies with ~GeV/m gradient
E_0=15MeV
ε_N=2mm-mrad
ζ_inj~1.5σ_zp~18cm
σ_ze~3mm~1.5λ_pe
η_trap~40%
E_mean~1.3GeV
ΔE/E_mean~12%
σ_r0=200μm
σ_r0=300μm
%/MeV
MeV
Lotov/Petrenko
P. Muggli, EuCard 03/29/2017

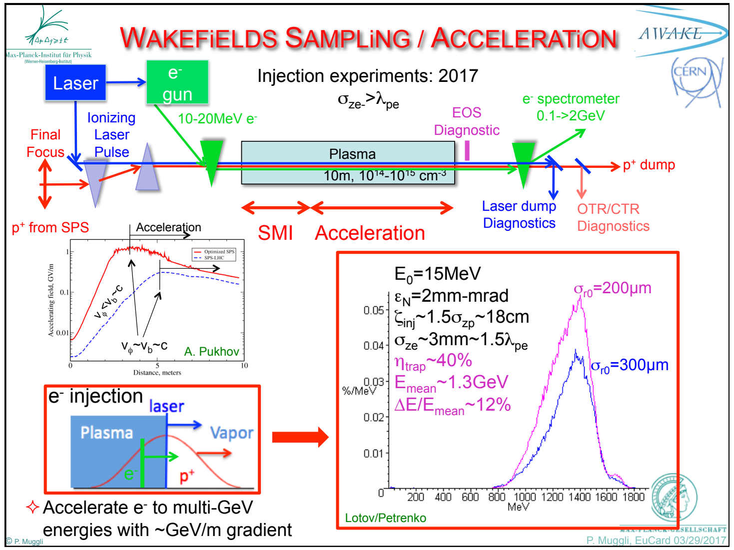

WAKEFIELDS SAMPLING / ACCELERATION
AWAKE
CERN
Laser
e- gun
Injection experiments: 2017
σze->λpe
e- spectrometer
0.1->2GeV
EOS
Ionizing
10-20MeV e-
2nd goal of AWAKE (2017-18):
Externally inject (~15MeV) electrons
into the wakefields
and
reach ~GeV energy gain with narrow ΔE/E
Vφ~Vb~c
Distance, meters
e- injection
laser
Plasma
Vapor
e-
p+
σze~3mm~1.5λpe
ηtrap~40%
Emean~1.3GeV
ΔE/Emean~12%
σr0=300μm
%/MeV
MeV
✧Accelerate e- to multi-GeV
energies with ~GeV/m gradient
P. Muggli, EuCard 03/29/2017

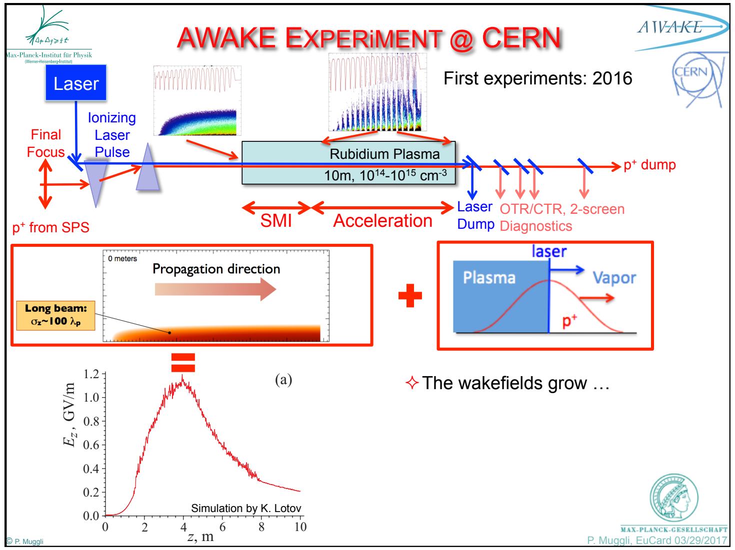

EXPERIMENTAL SETUP RUN II
AWAKE
CERN
Laser
e- gun
rf gun
10-20MeV e-
e- spectrometer
10+GeV
Ionizing
Laser
Pulse
Final
Focus
Plasma
~4m
Plasma
~10+m
p+ dump
p+ from SPS
SMI
Seeding
Laser
OTR/CTR
Diagnostics
Acceleration
Discharge/Helicon
OTR/CTR
Diagnostics
N. Lopes
TÉCNICO LISBOA
Imperial College London
O. Grülke
L=10m
helicon antenna
water-cooled
field coils
✧ Laser ionization of a metal vapor (Rb), 3-4m plasma for p+ SMI only, SEEDING NECESSARY!
✧~10m discharge or helicon source for acceleration only (scales to 100's m)
✧Inject short e- bunch (σz<<λpe), quality of the bunch (ΔE/E, ε)
✧Density step to maintain accelerating gradient
✧2021-LS3, RUN II
P. Muggli, EuCard 03/29/2017


SUMMARY
AWAKE
CERN
✧ AWAKE is a p+-driven PWFA experiment
✧ AWAKE aims at ~1GeV/m gradient using the self-modulation instability of a long p+ bunches in a plasma (σz>>λpe)
✧ AWAKE ran for 48h in Dec. 2016 and saw signs of SMI on all three diagnostics
✧ SMI and e- acceleration demo experiments in 2017-18
✧ Run II: (2021-): quality of the accelerated e- bunch (ΔE/E, ε)
✧ AWAKE has a helicon plasma source development project with IPP/SPC for 1-4-10-100s m source …
✧ Application of p+-driven-PWFA: e-/p+ collisions
E. Gschwendtner et al., Nucl. Instr. and Meth. in Phys. Res. A 829, 76 (2016).
E. Öz et al., Nucl. Instr. and Meth. in Phys. Res. A 829, 321 (2016).
E. Öz et al., Nucl. Instr. Meth. Phys. Res. A 740(11), 197 (2014).
A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463.
A. Caldwell et al., AWAKE Coll., Nucl. Instrum. A 829 (2016) 3
(c)
LHC
Ez,max, GV/m
L, m
Caldwell PoP, 2011
P. Muggli, EuCard 03/29/2017


Thank you to my collaborators
Thank you!
http://www.mpp.mpg.de/~muggli
muggli@mpp.mpg.de


Rb VAPOR/PLASMA SOURCE
Instrumentation
AWAKE
F. Braunmueller, MPP
R. Speroni, CERN
WDL
79 temperature probes for controlling 15 heater sections
8 control valves for loss of pressure and experiment requirements
✧Somewhat complex control system
✧Worked well
✧Produced expected Rb vapor density
✧No safety incident with Rb
Vapour cell
Expansion volume
Oil heater
Rb-flask and flow path
P. Muggli, EuCard 03/29/2017


WAKEFIELDS SAMPLING / ACCELERATION
AWAKE
Laser
e⁻ gun
Injection experiments: 2017
σze->λpe
Ionizing Laser Pulse
10-20MeV e⁻
EOS Diagnostic
e⁻ spectrometer 0.1->2GeV
Final Focus
Plasma
10m, 10¹⁴-10¹⁵ cm⁻³
p⁺ dump
Laser dump Diagnostics
OTR/CTR Diagnostics
p⁺ from SPS
SMI
Acceleration
A. Pukhov
e⁻ injection
laser
Plasma
Vapor
E0=15MeV
εN=2mm-mrad
ξinj~1.5σzp~18cm
σze~3mm~1.5λpe
ηtrap~40%
Emean~1.3GeV
ΔE/Emean~12%
σr0=200µm
σr0=300µm
%/MeV
MeV
Lotov/Petrenko
✧Accelerate e⁻ to multi-GeV energies with ~GeV/m gradient
P. Muggli, EuCard 03/29/2017


AWAKE EXPERIMENT @ CERN
AWAKE
Laser
First experiments: 2016
Ionizing Laser Pulse
Final Focus
Rubidium Plasma
10m, 10¹⁴-10¹⁵ cm⁻³
p⁺ dump
p⁺ from SPS
SMI
Acceleration
Laser Dump
OTR/CTR, 2-screen Diagnostics
Propagation direction
Long beam: σz~100 λp
laser
Plasma
Vapor
p⁺
(a)
Ez, GV/m
z, m
Simulation by K. Lotov
✧The wakefields grow …
P. Muggli, EuCard 03/29/2017