Status and first results from AWAKE

(for the AWAKE Collaboration)

Patric Muggli
***Max Planck Institute for Physics*, Munich**
CERN
muggli@mpp.mpg.de
https://www.mpp.mpg.de/~muggli

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

MAX-PLANCK-GESELLSCHAFT

AWAKE for 48 hours!

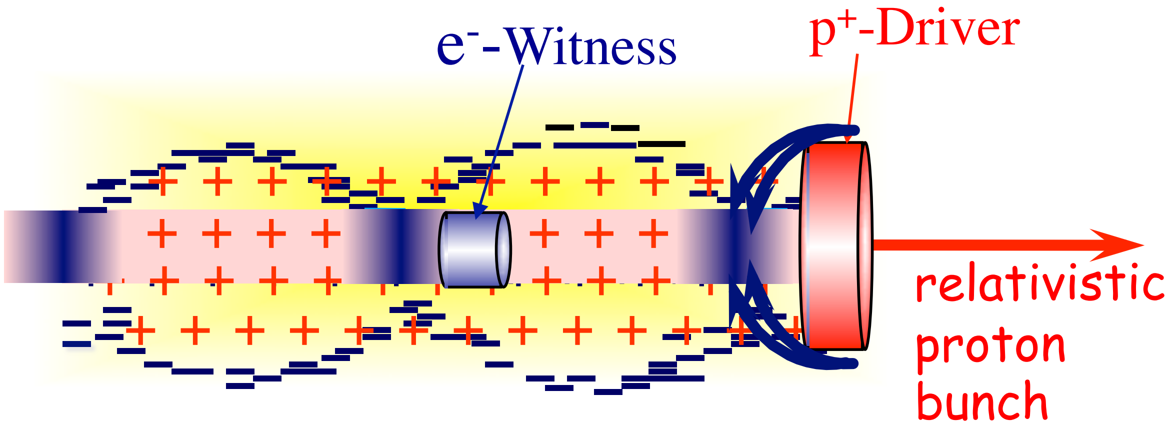
The first results!

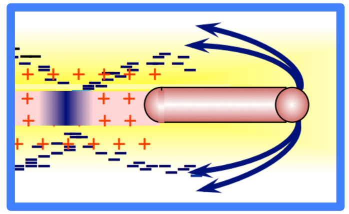
(for the AWAKE Collaboration)

Patric Muggli
Max Planck Institute for Physics, **Munich**
CERN
muggli@mpp.mpg.de
https://www.mpp.mpg.de/~muggli

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)
MAX-PLANCK-GESELLSCHAFT

p⁺-DRiVEN PWFA



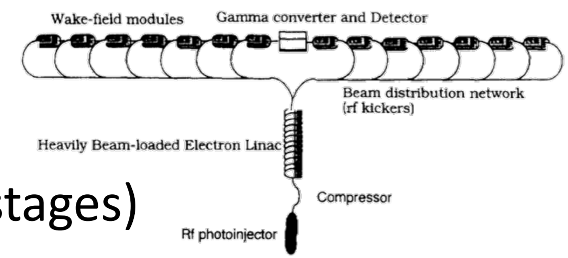


✧ILC-CLIC, 0.5TeV bunch with $2\times10^{10}e^-$ ~1.6kJ

✧SLAC, 20GeV bunch with $2\times10^{10}e^-$ ~60J

✧SLAC-like driver for staging (FACET= 1 stage, collider 10^+ stages)

J. Rosenzweig et al. /Nucl. Instr. and Meth. in Phys. Res. A 410 (1998) 532–543

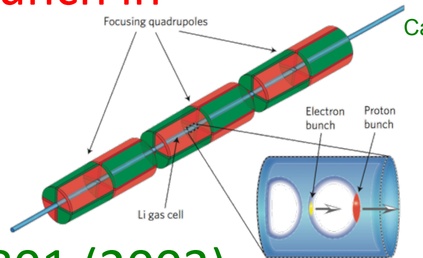


✧SPS, 400GeV bunch with $10^{11}p^+$ ~6.4kJ
LHC, 7TeV bunch with $10^{11}p^+$ ~112kJ

✧A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage!

✧Large average gradient! (≥1GeV/m, 100's m)

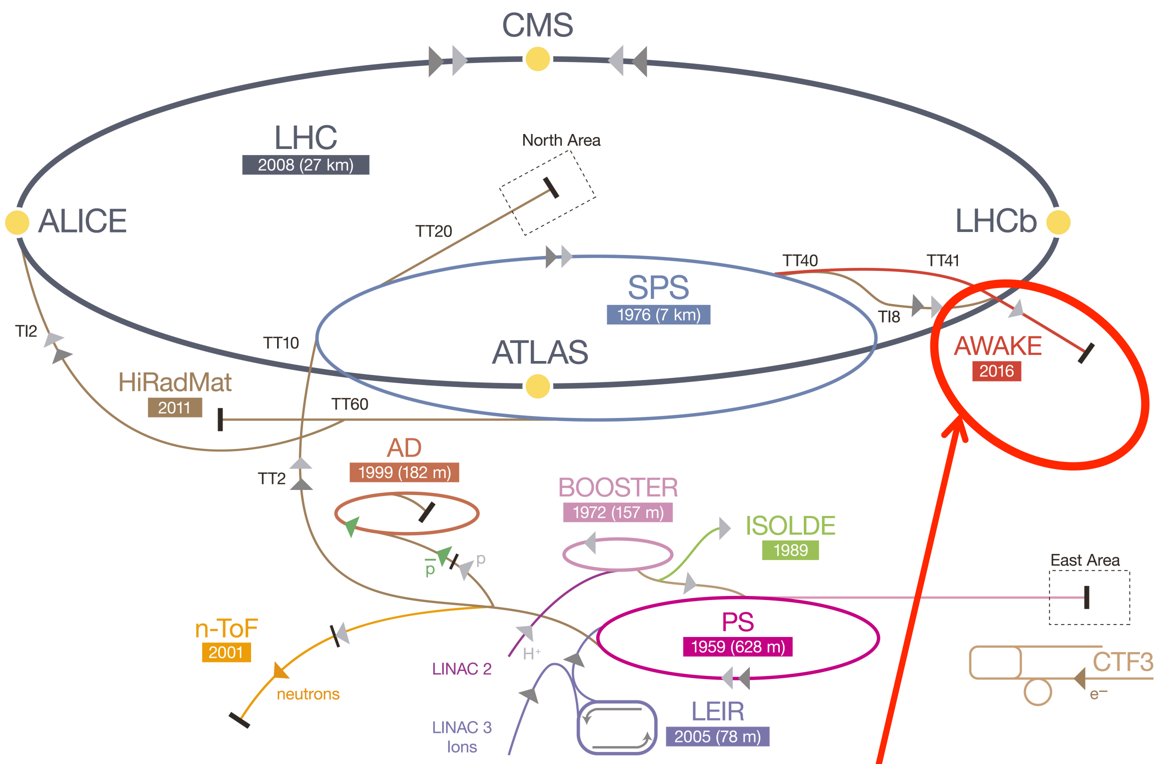
✧Wakefields driven by e⁺ bunch: Blue, PRL 90, 214801 (2003)



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

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^*

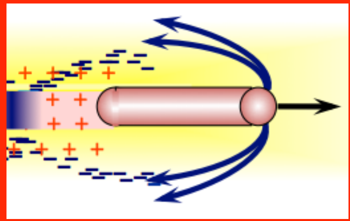
PROTON BEAMS @ CERN

CERN's Accelerator Complex

CMS

Parameter	PS	SPS	SPS Opt

Scaling



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

$\sigma_z=12cm\sim\lambda_{pe} \rightarrow n_e\sim 8x10^{10}cm^{-3}$

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

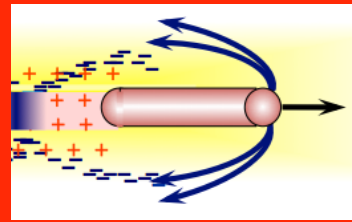
PROTON BEAMS @ CERN

CERN's Accelerator Complex

CMS

Parameter	PS	SPS	SPS Opt

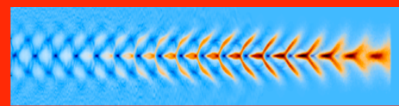
Scaling



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

$\sigma_z=12cm\sim\lambda_{pe} \rightarrow n_e\sim 8x10^{10}cm^{-3}$

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



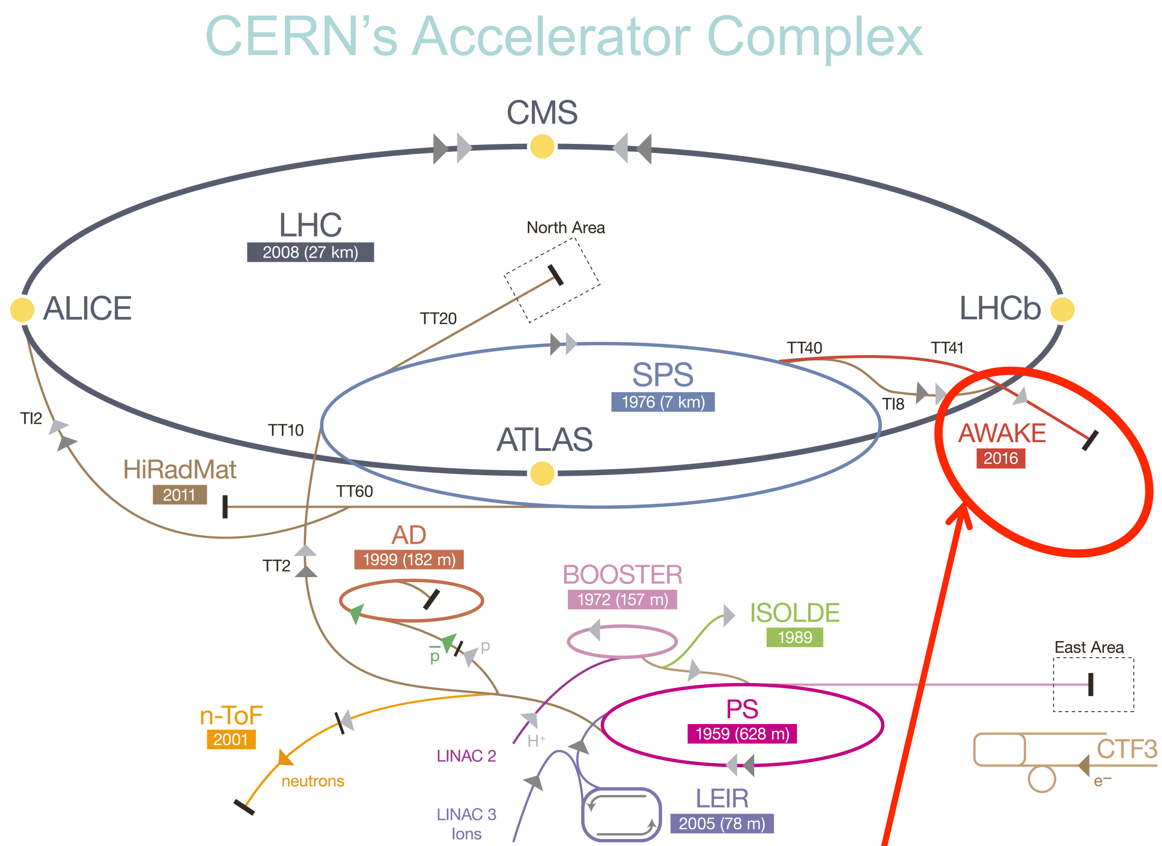
→Use self-modulation instability (SMI)

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

$\rightarrow n_e\sim 7x10^{14}cm^{-3}$, $(k_{pe}\sigma_r=2\pi\sigma_r/\lambda_{pe}\sim 1)$

$\rightarrow E_{WB}\sim 1GV/m$, $f_{pe}\sim 237GHz$, $L_p=10m$

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

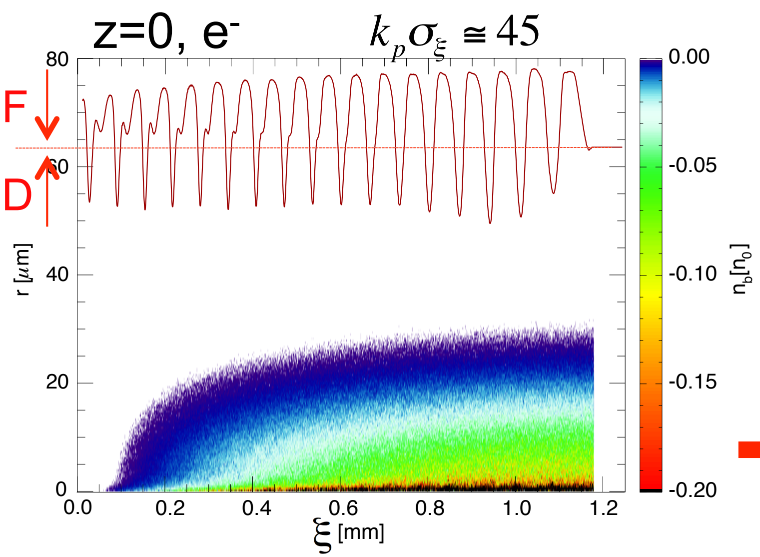
AWAKE experimental area

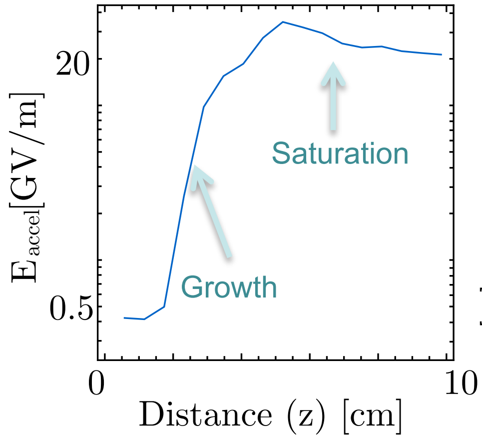
n_e~7×10^{14}cm^{-3} for $k_p\sigma_r\approx1$
λ_{pe}~1.2mm<<σ_z
f_{pe}~240GHz
L_p~10m~$2\beta^*$

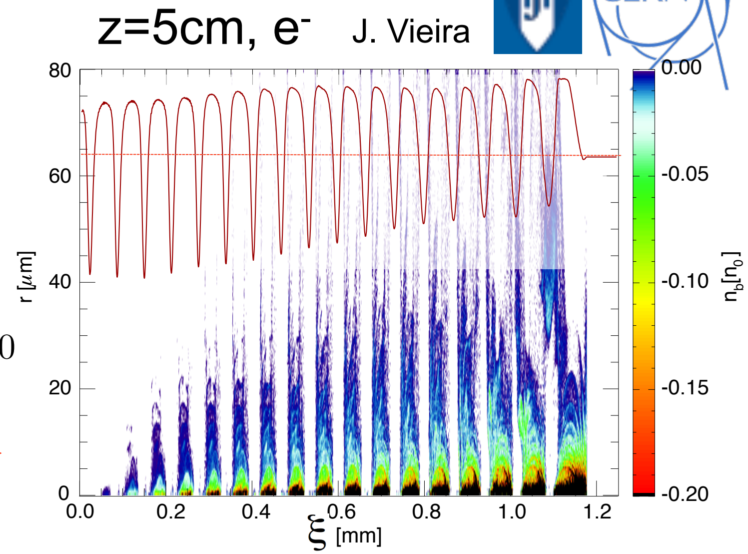
✧SPS beam: high energy, small σ_r^*, long β^*

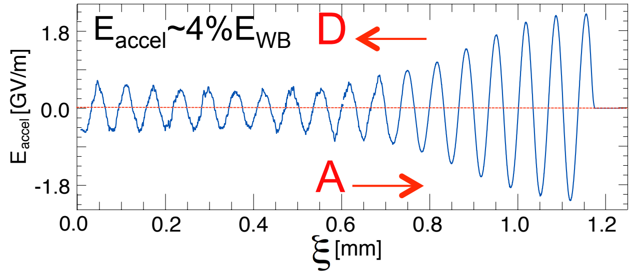
✧Initial goal: ~GeV gain by externally injected e^-, in 5-10m of plasma in self-modulated p^+ driven PWFA

SELF-MODULATiON INSTABiLiTY (SMI)

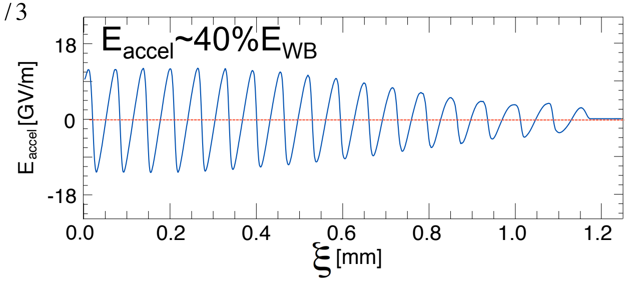








$$N_{exp} \cong \frac{3\sqrt{3}}{4}\left(\frac{n_b}{n_e}\frac{m_e}{\gamma M_b}\left(k_p|\xi|\right)\left(k_p z\right)^2\right)^{1/3}$$



Grows along the bunch & along the plasma

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

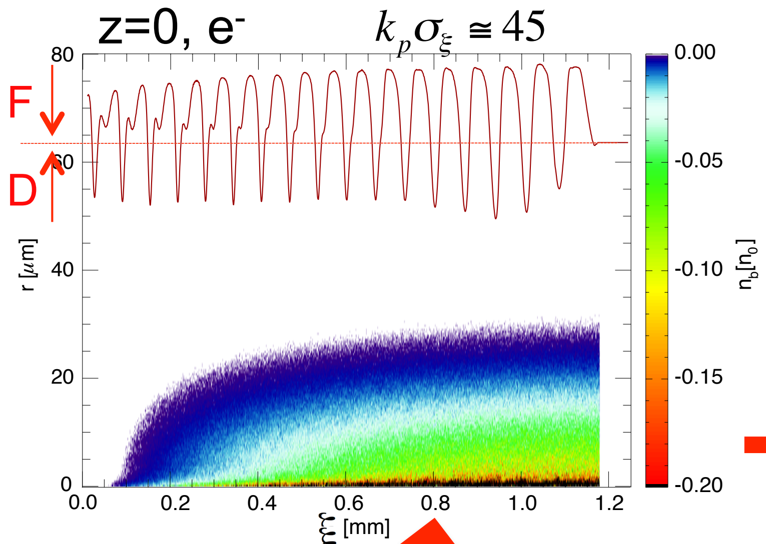
J. Vieira et al., Phys. Plasmas 19, 063105 (2012)

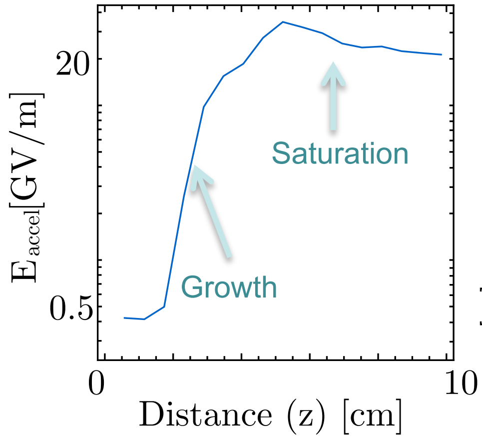
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

SELF-MODULATION INSTABILITY (SMI)

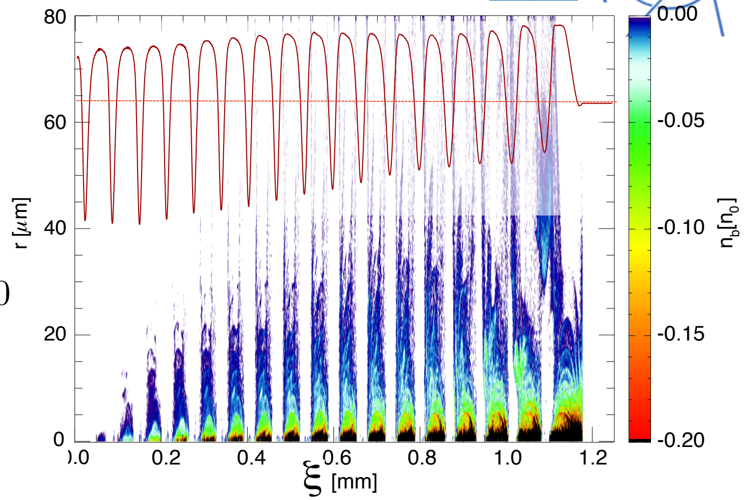
AWAKE

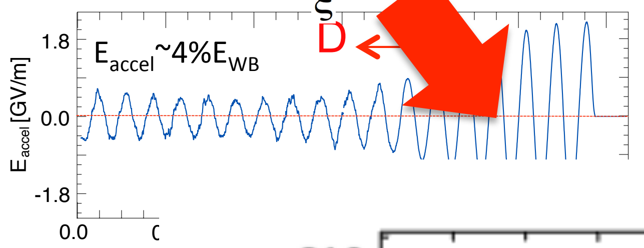
CERN

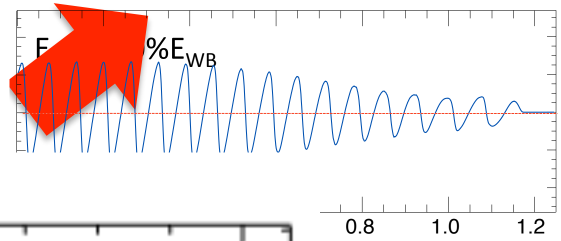




J. Vieira

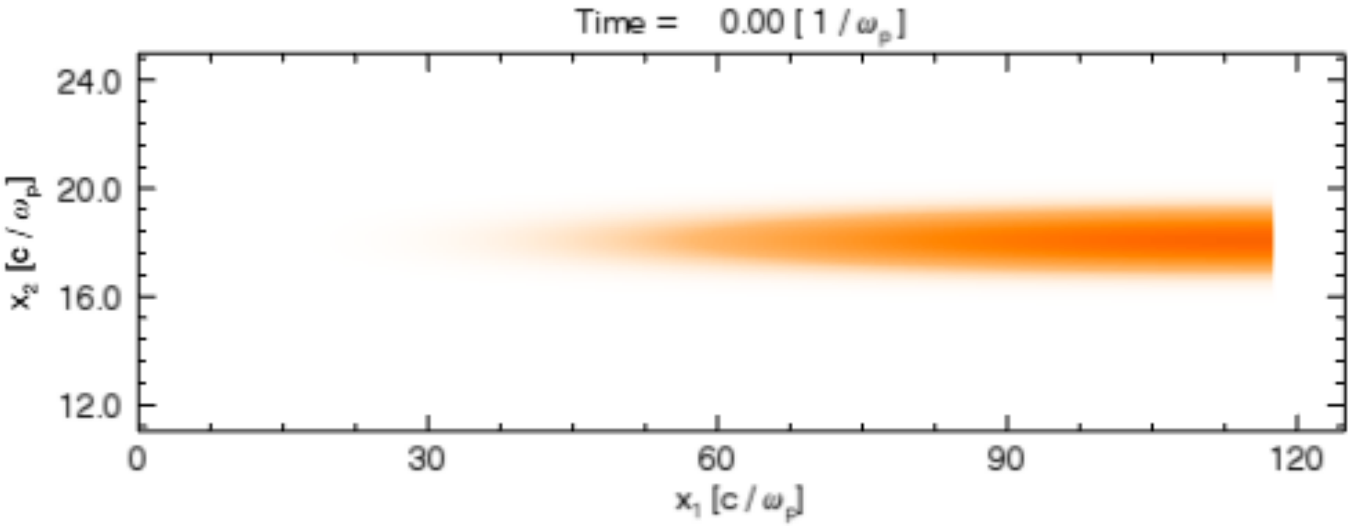






Radial!

NOT longitudinal!

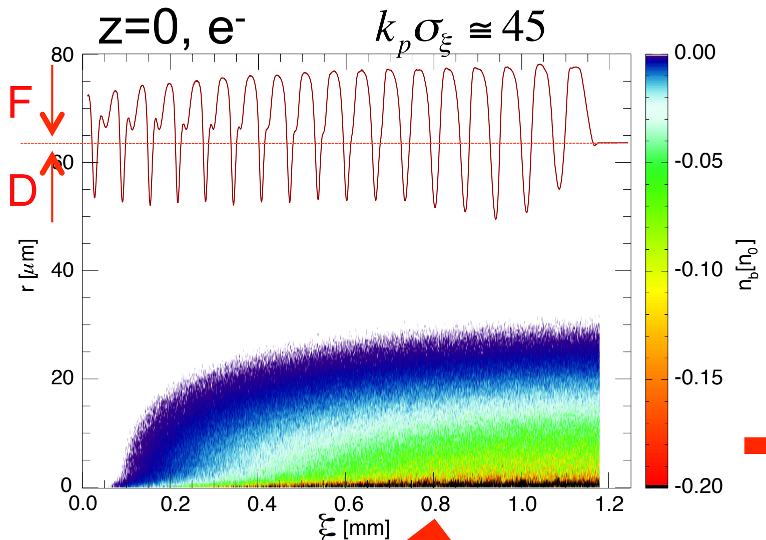


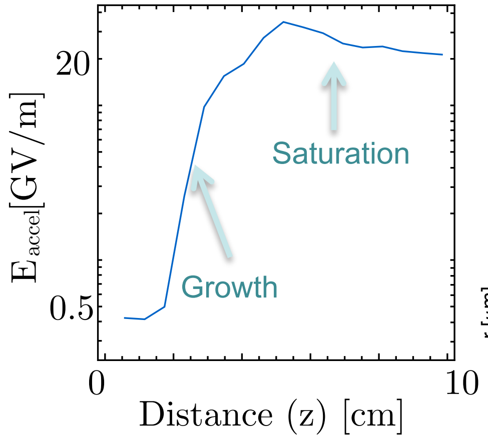
2D Slab, e-

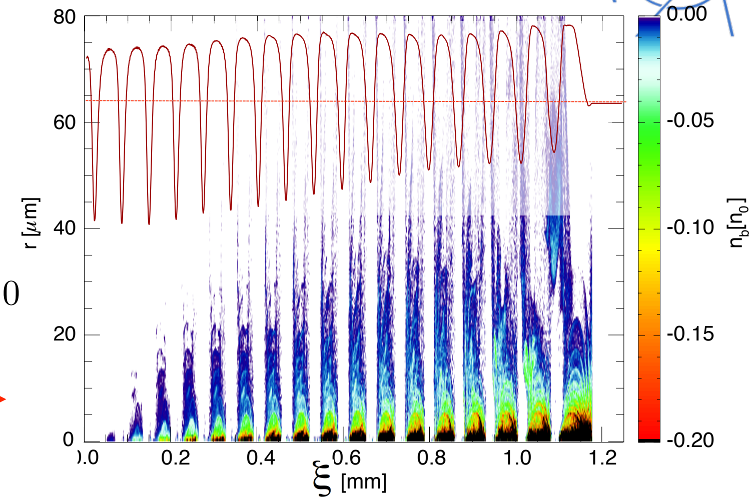
MAX-PLANCK-GESELLSCHAFT

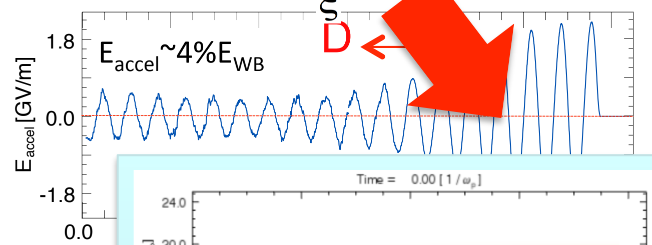
SELF-MODULATION INSTABILITY (SMI)

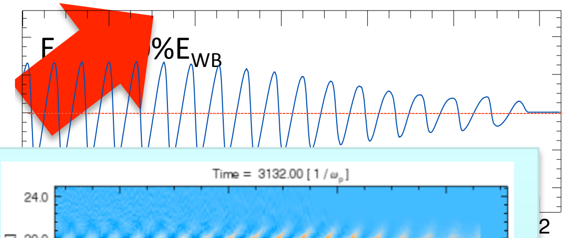
Vieira, Phys. Plasmas 19, 063105 (2012).





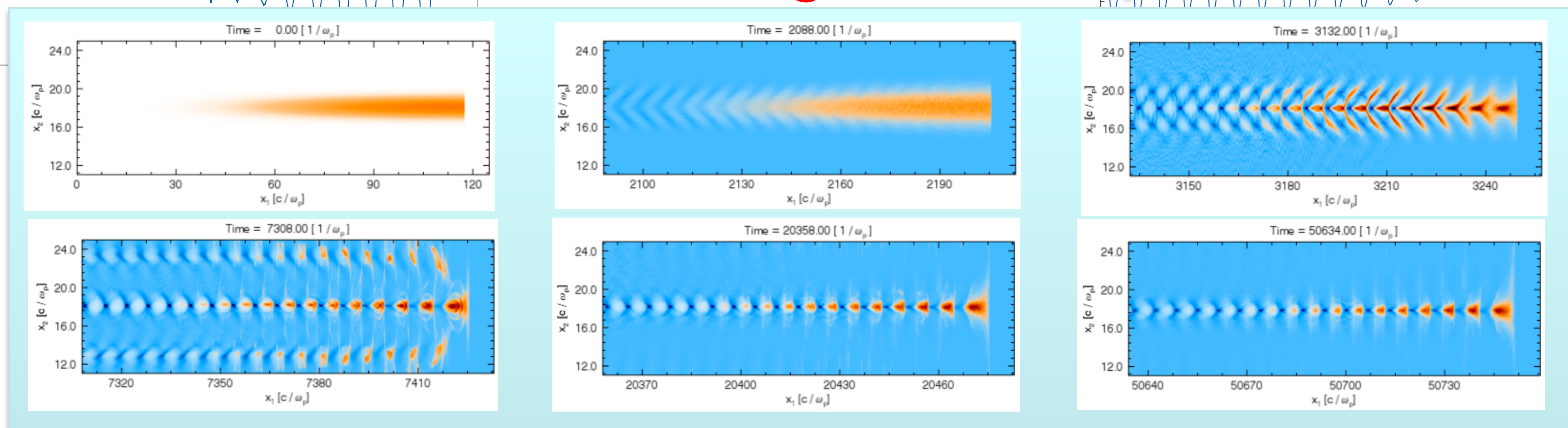






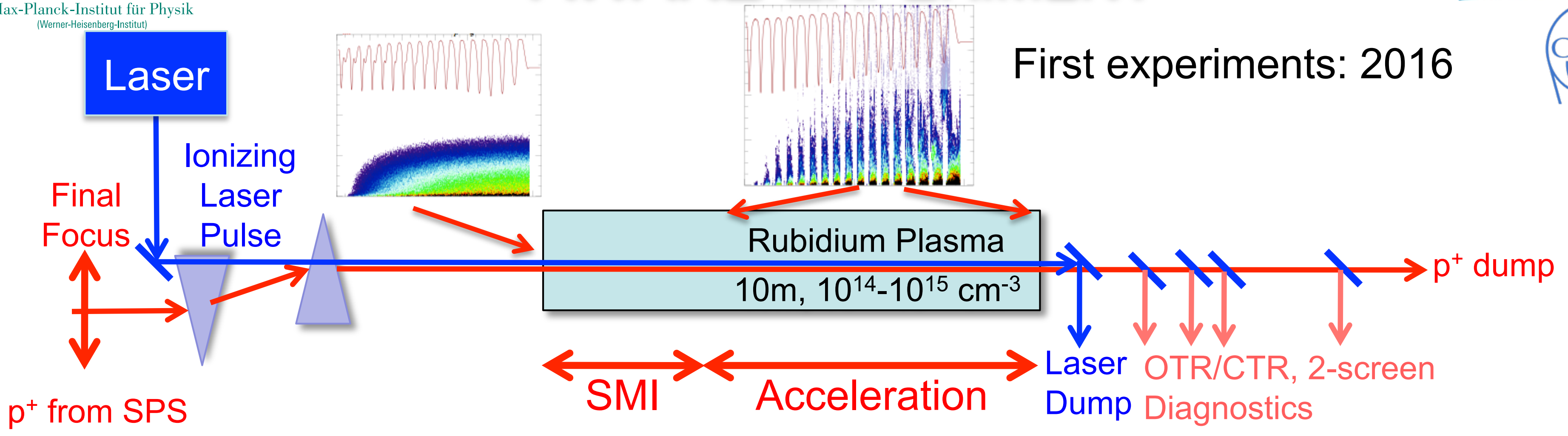
Radial!

NOT longitudinal!

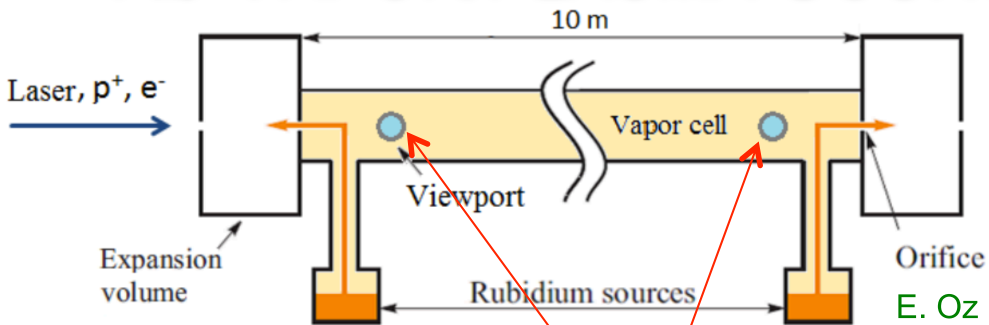


AWAKE EXPERIMENT

First experiments: 2016



Rb VAPOR/PLASMA SOURCE

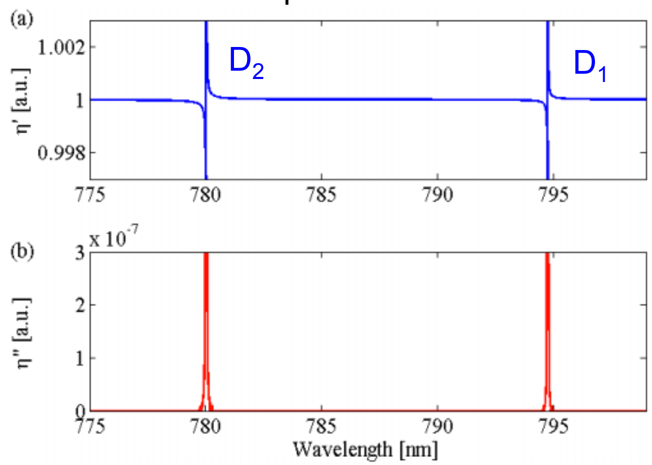


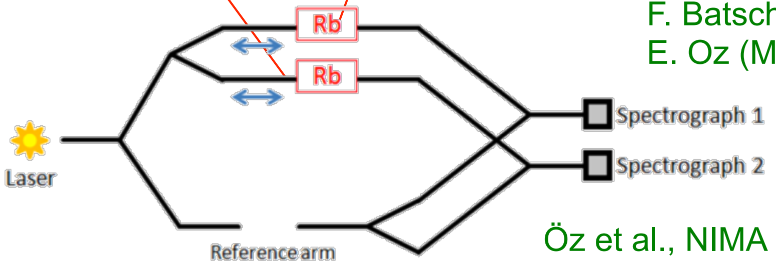
R. Kersevan (CERN)
G. Plyushchev (CERN/MPP/EPFL)

E. Oz & P. Muggli., NMA 740(11), 197 (2014).

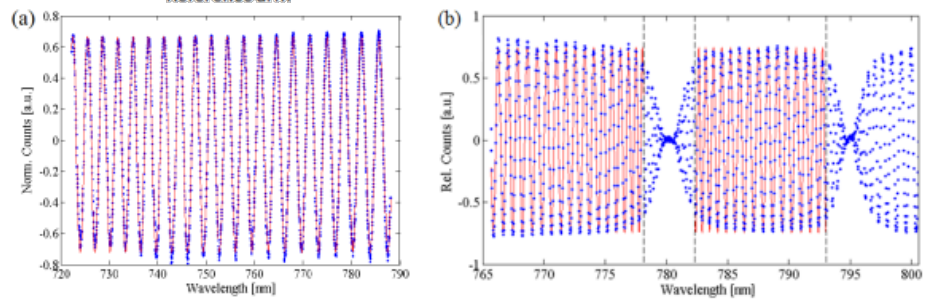
F. Batsch (MPP)
E. Oz (MPP)

Rb anomalous dispersion at 780 and 794nm

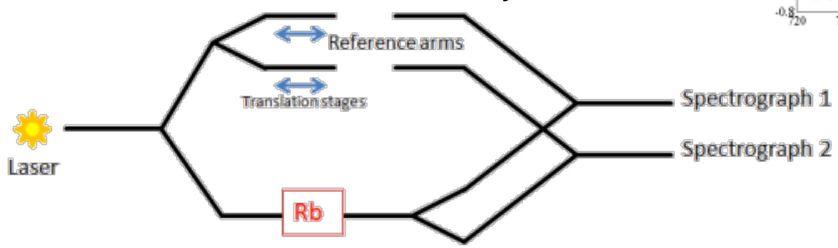




Öz et al., NIMA 829, 321 (2016)



Test relative accuracy

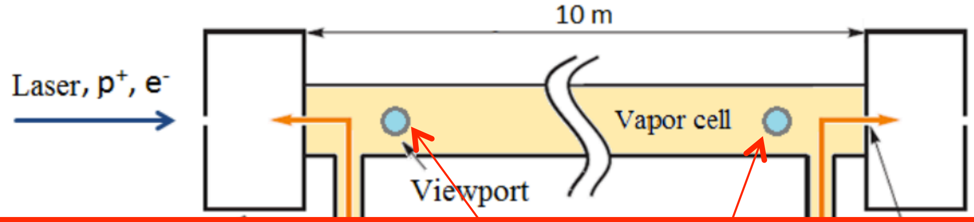


$$S(\lambda) = \tilde{A} \cdot \cos\left(\frac{2\pi}{\lambda} \cdot \left[\frac{\tilde{n}l \, r_0 f_1 \lambda_1^3}{4\pi(\lambda-\lambda_1)} + \frac{\tilde{n}l \, r_0 f_2 \lambda_2^3}{4\pi(\lambda-\lambda_2)} + \tilde{\xi}\right]\right)$$

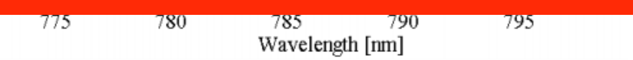
- ✧Requirements: $10^{14}<n_{Rb,e}<10^{15}$cm^{-3}, $\Delta n_{Rb,e}/n_{Rb,e}<0.2\%$, few cm $n_{Rb,e}$ ramp
- ✧Impose temperature ΔT<0.3K @500K ($\Delta T/T=\Delta n_{Rb}/n_{Rb}<0.2\%$) + free expansion at ends
- ✧Anomalous dispersion for n_{Rb} measurement: <0.3% accuracy!
- ✧Meets all specs …

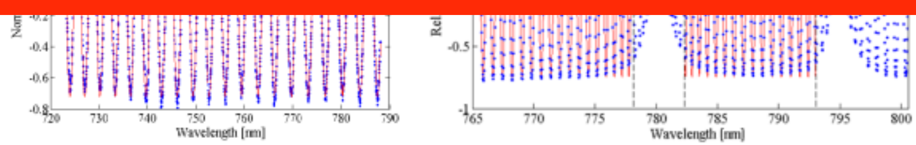
Rb VAPOR/PLASMA SOURCE

R. Kersevan (CERN)
G. Plyushchev (CERN/MPP/EPFL)

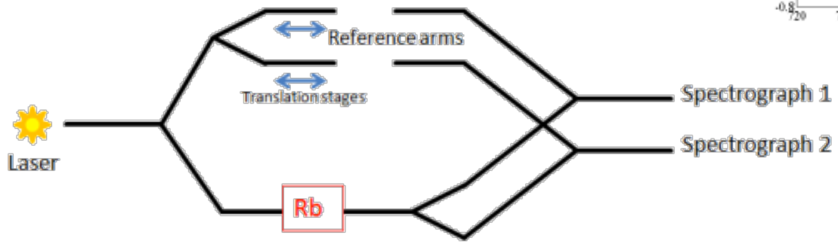


See Fabian's talk … (n_{Rb})





Test relative accuracy



$$S(\lambda) = \tilde{A}\cdot\cos\left(\frac{2\pi}{\lambda}\cdot\left[\frac{\tilde{n}l\cdot r_0 f_1\lambda_1^3}{4\pi(\lambda-\lambda_1)} + \frac{\tilde{n}l\cdot r_0 f_2\lambda_2^3}{4\pi(\lambda-\lambda_2)} + \tilde{\xi}\right]\right)$$

- ✧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 $\Delta T<0.3$K @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 …

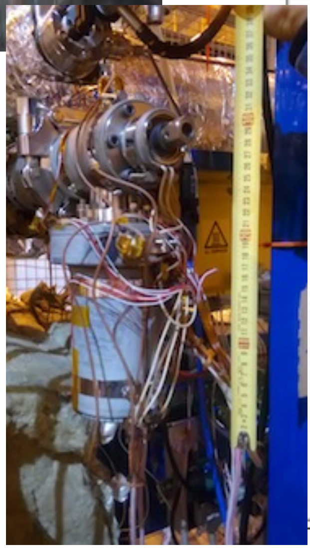
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

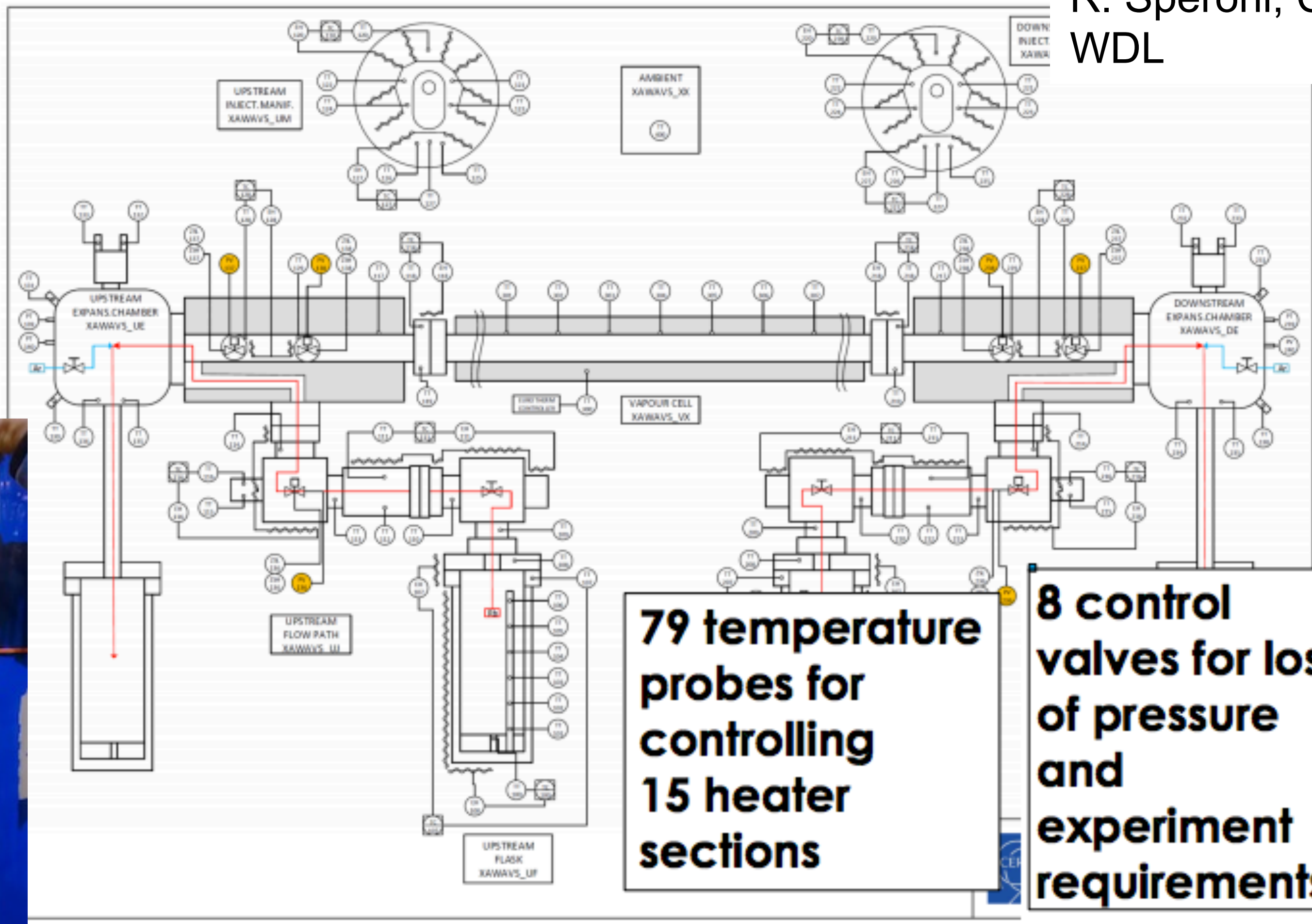
AWAKE

Rb VAPOR/PLASMA SOURCE

Instrumentation

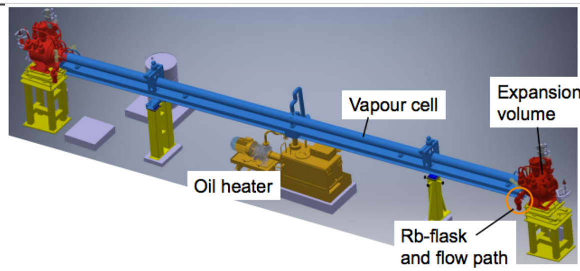
F. Braunmueller, MPP
R. Speroni, CERN
WDL





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

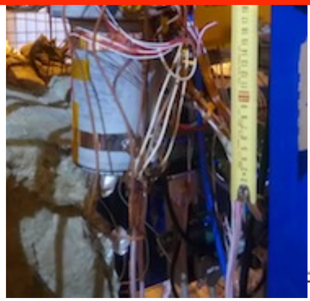
MAX-PLANCK-GESELLSCHAFT

Rb VAPOR/PLASMA SOURCE

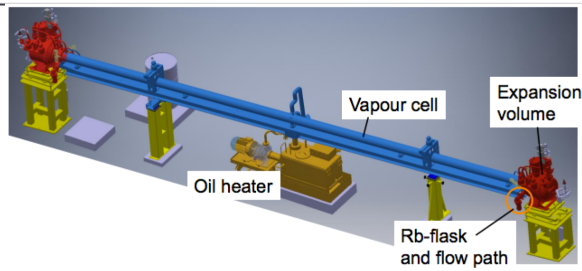
Instrumentation

F. Braunmueller, MPP
R. Speroni, CERN
WDL

See Falk's talk …

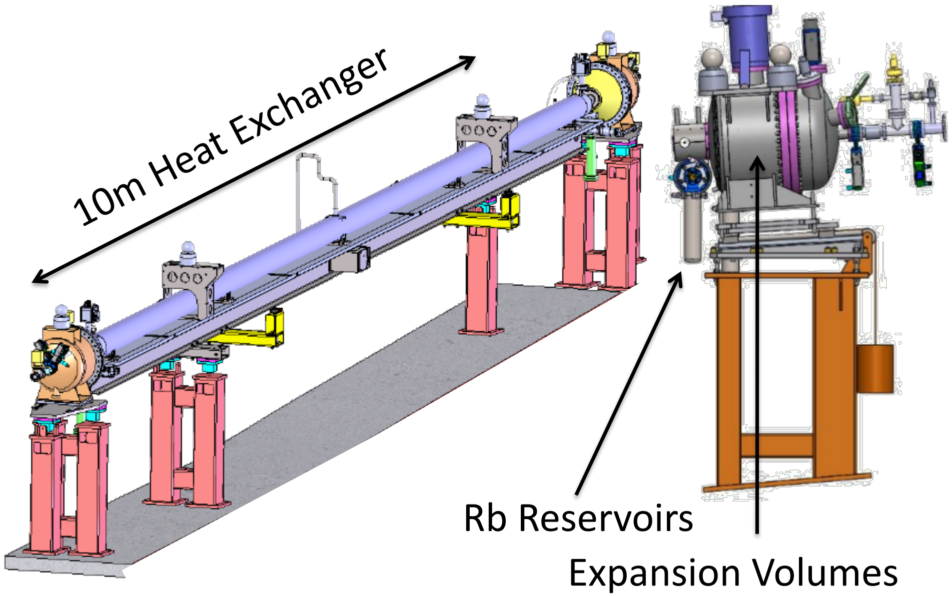


- ✧Somewhat complex control system
- ✧Worked well
- ✧Produced expected Rb vapor density
- ✧No safety incident with Rb

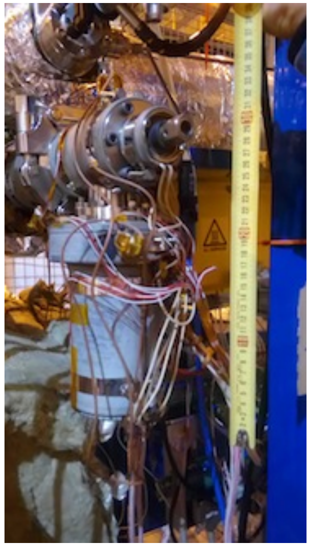


Rb VAPOR SOURCE (heat exchanger)

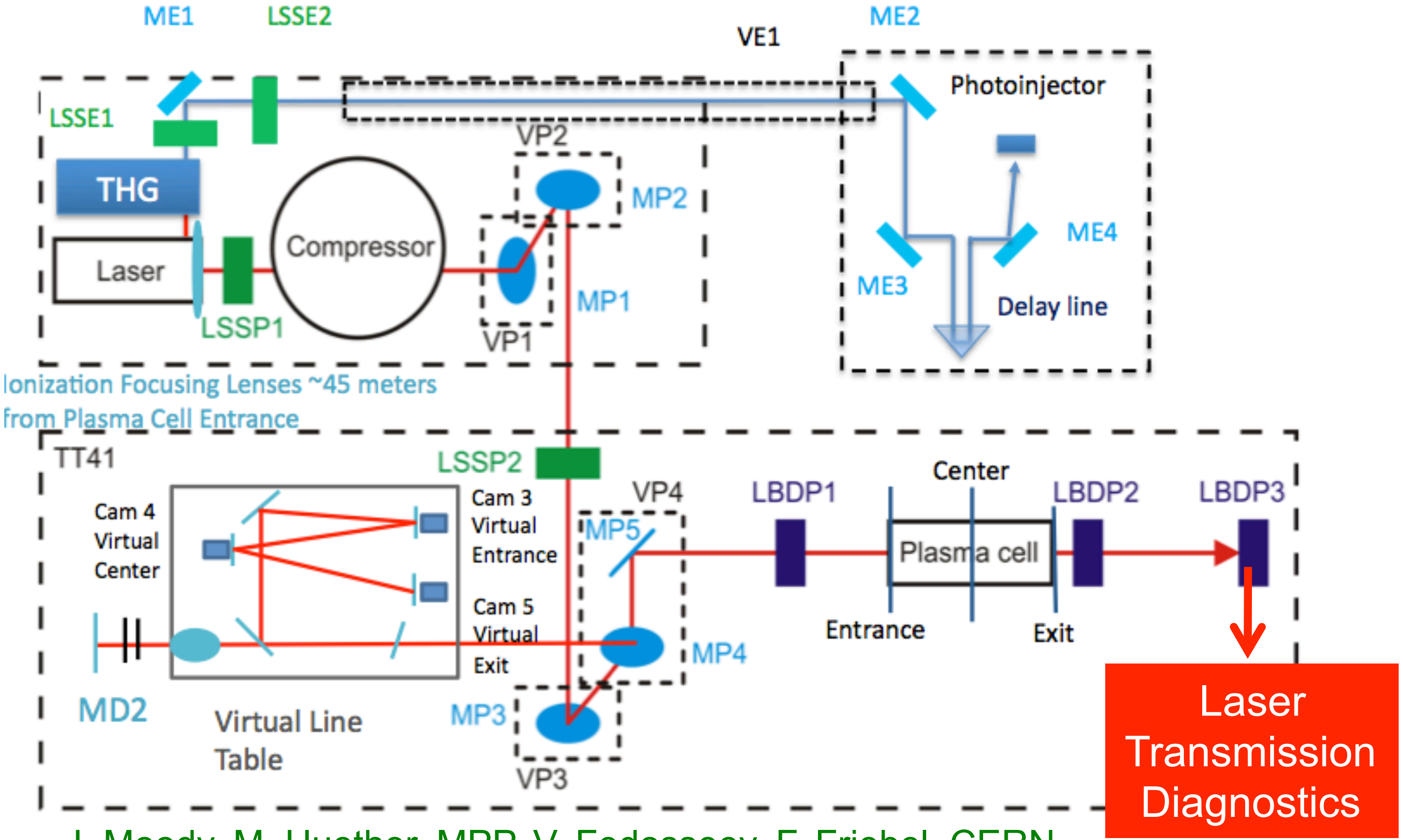
Development of the ends



Installed in AWAKE!



LASER & PLASMA

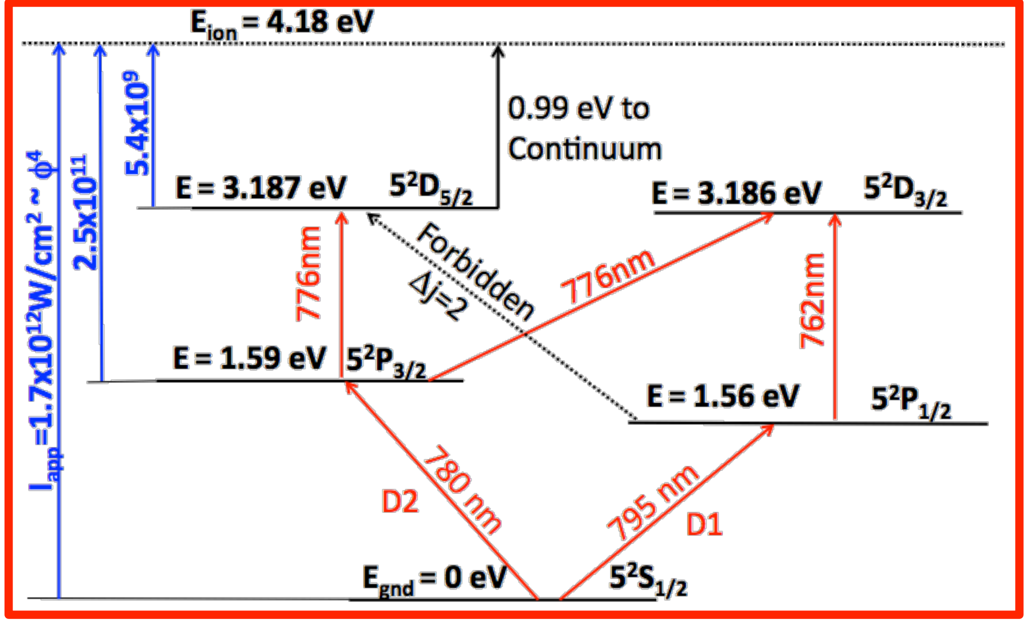


J. Moody, M. Huether, MPP, V. Fedosseev, F. Friebel, CERN

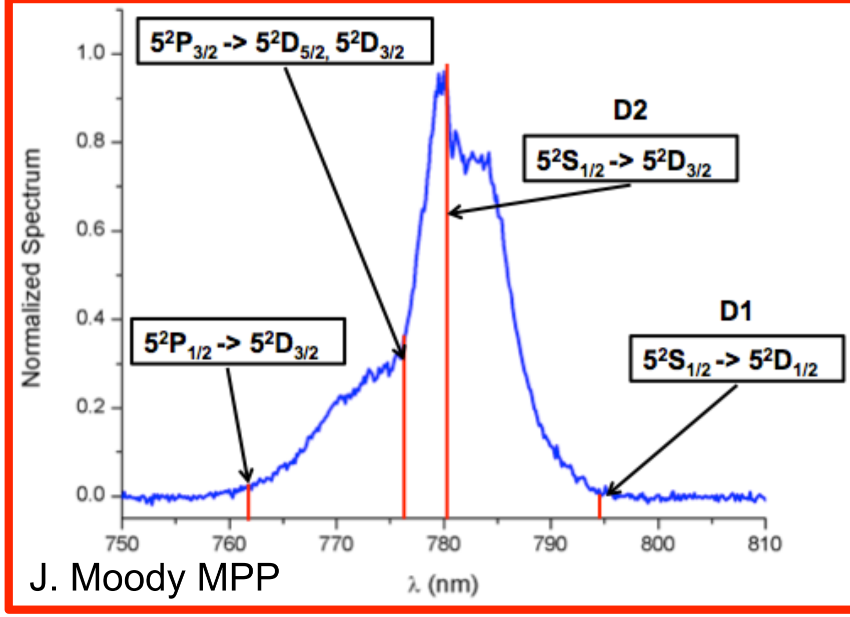
- ✧Fiber/Ti-Sapphire laser: ~100fs, E_{max}=450mJ
- ✧Rb: ϕ_{IP}=4.177eV, I_{app}~1.7×10^{12}Wcm^{-2},
- ✧r_0~1mm, Z_R~5m, I_{max}>10×10^{12}Wcm^{-2}
- ✧Field ionization => n_e=n_{Rb}, uniformity and ramps
- ✧Virtual plasma for alignment

Laser & Plasma Challenges

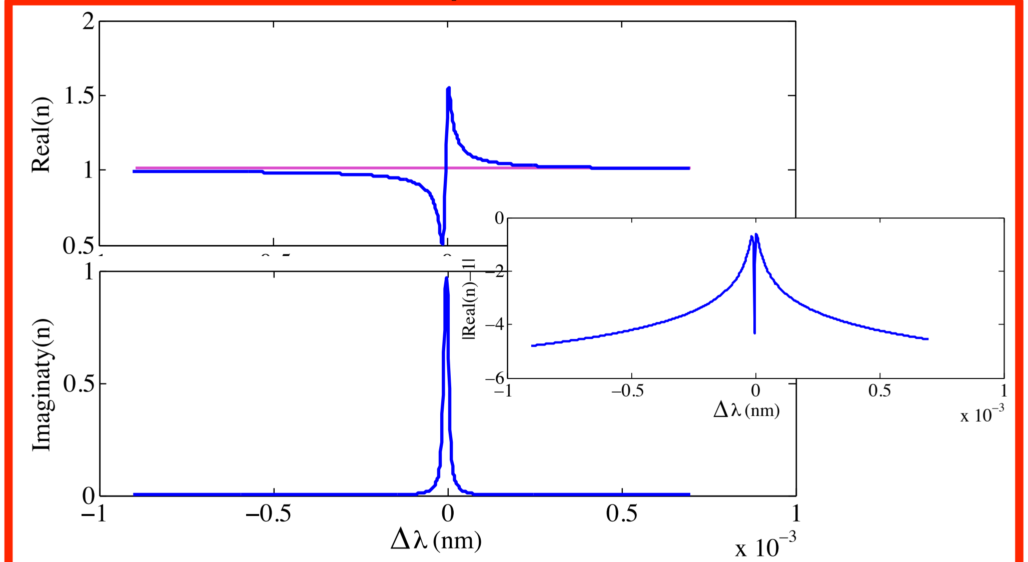
Rubidium I Grotian Diagram



Laser Pulse Spectrum (~100fs)



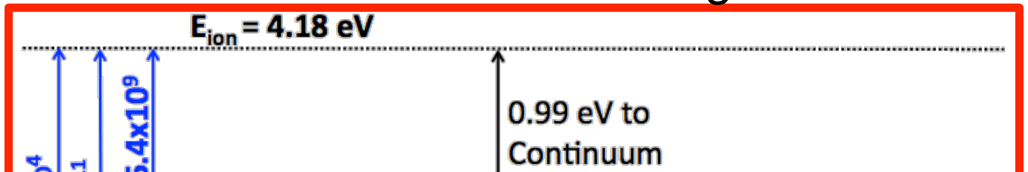
Anomalous Dispersion D1/D2 Lines



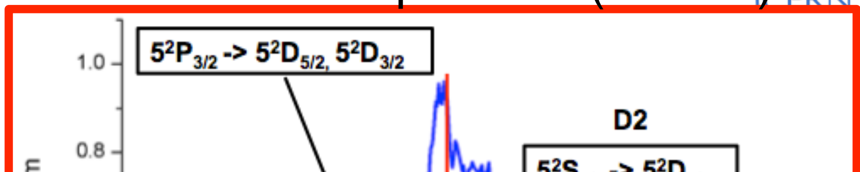
- Overlap between Rb optical transitions (D_2 @ 780nm) and short laser pulse spectrum
- Anomalous dispersion can stretch the pulse, dominates interaction
- Population of upper states decreases ionization intensity
- Why we are here …
- See Josh's talk

LASER & PLASMA CHALLENGES

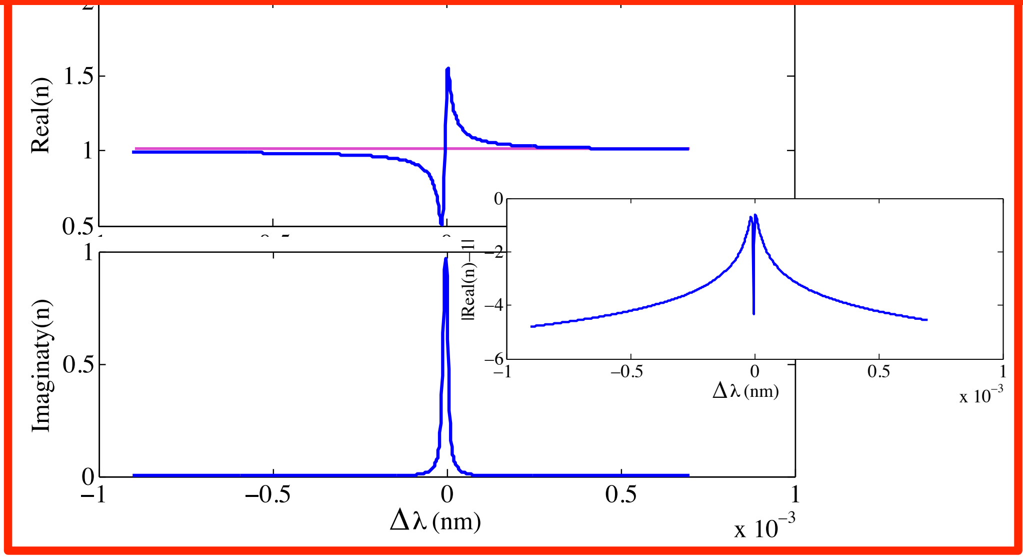
Rubidium I Grotian Diagram



Laser Pulse Spectrum (~100fs)

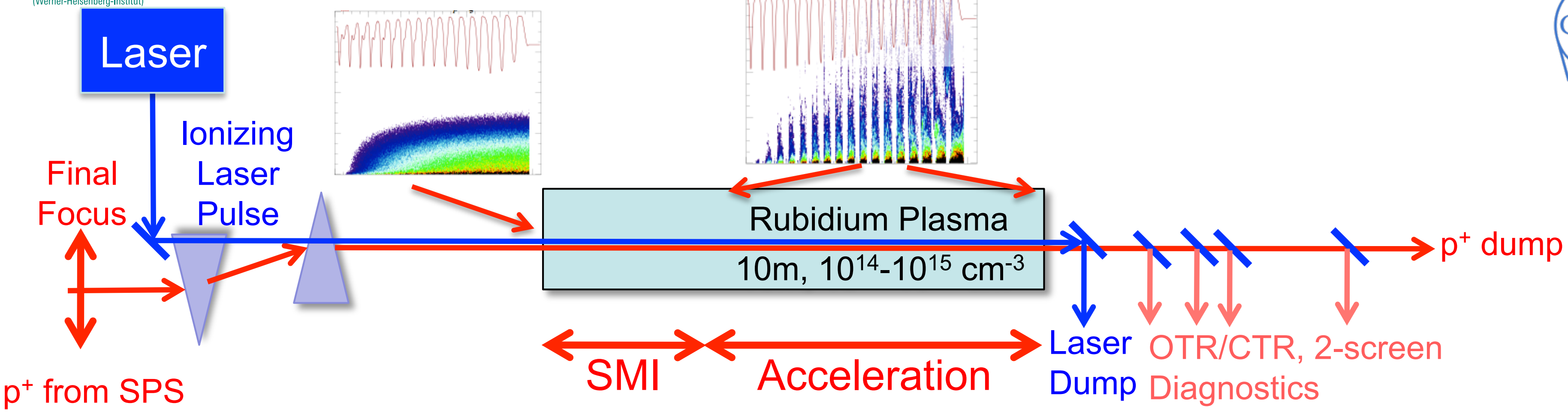


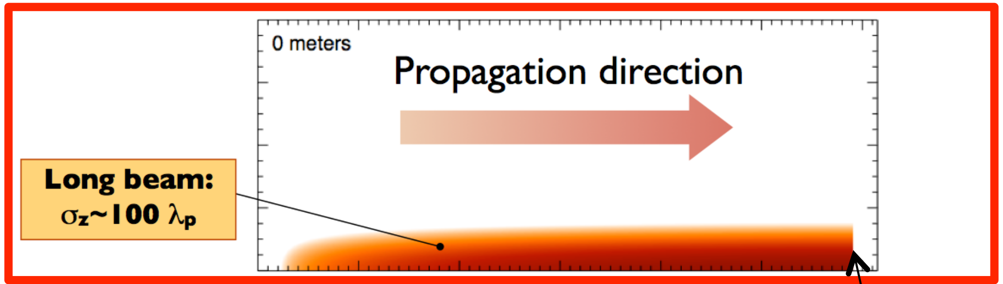
See Josh's and Gabor's talk …
See Anna-Maria's talk … (wakefields)
and Misha's talks … (n_e)

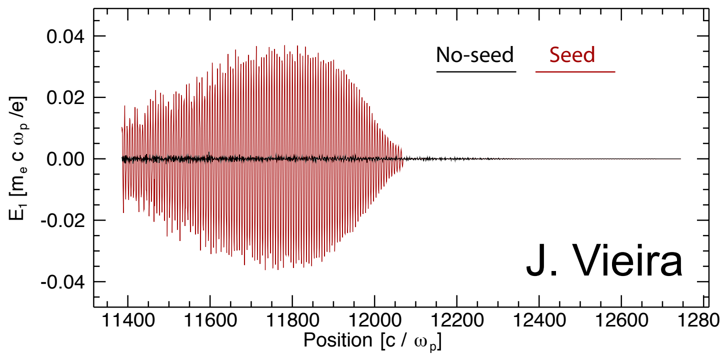


- Overlap between Rb optical transitions (D_2 @ 780nm) and short laser pulse spectrum
- Anomalous dispersion can stretch the pulse, dominates interaction
- Population of upper states decreases ionization intensity
- Why we are here …
- See Josh's talk

AWAKE EXPERiMENT @ CERN







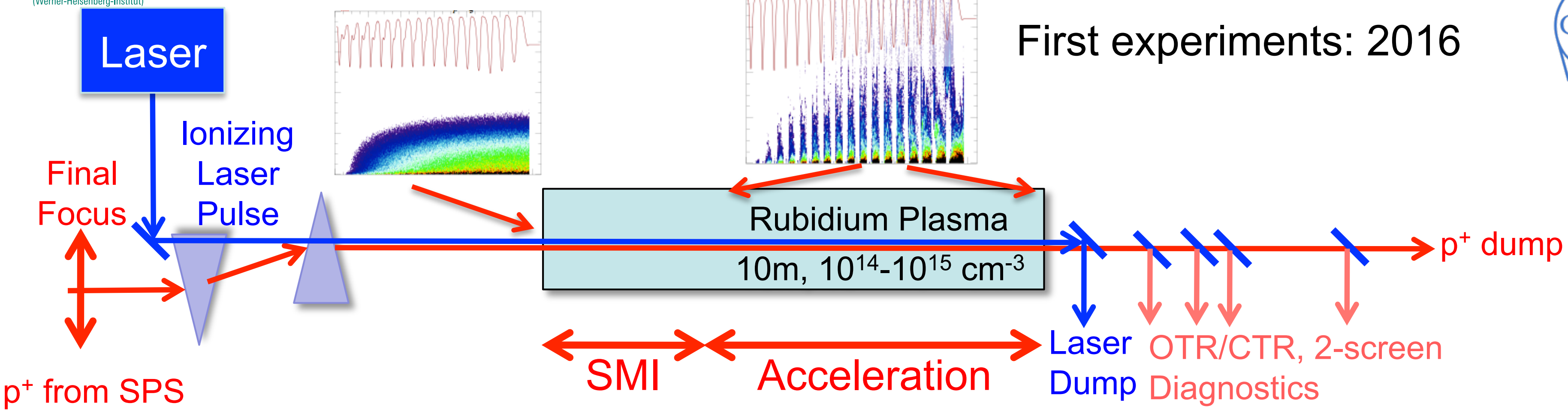
✧No seed no SMI (over 10m)

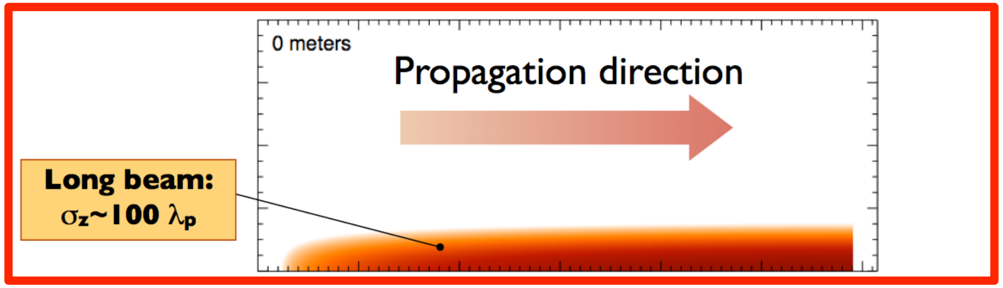
"Sharp" ($<<\lambda_{pe}$) start of the beam/plasma interaction for SMI seeding

AWAKE: will seed with ionization front!

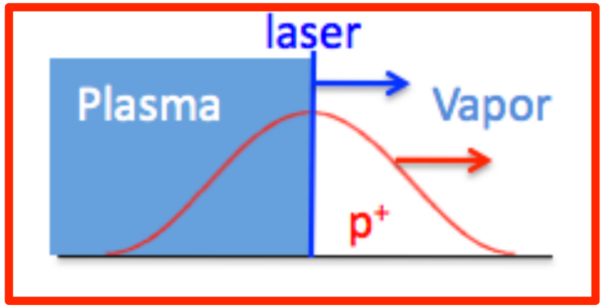
AWAKE EXPERIMENT @ CERN

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<<λ_{pe} => good seed

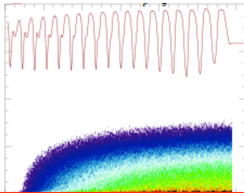
*Kumar, Phys. Rev. Lett. 104, 255003 (2010)

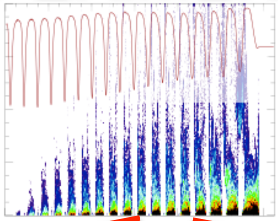
AWAKE EXPERIMENT @ CERN

First experiments: 2016

Laser

Ionizing





See Mathias's talks … (seeding)

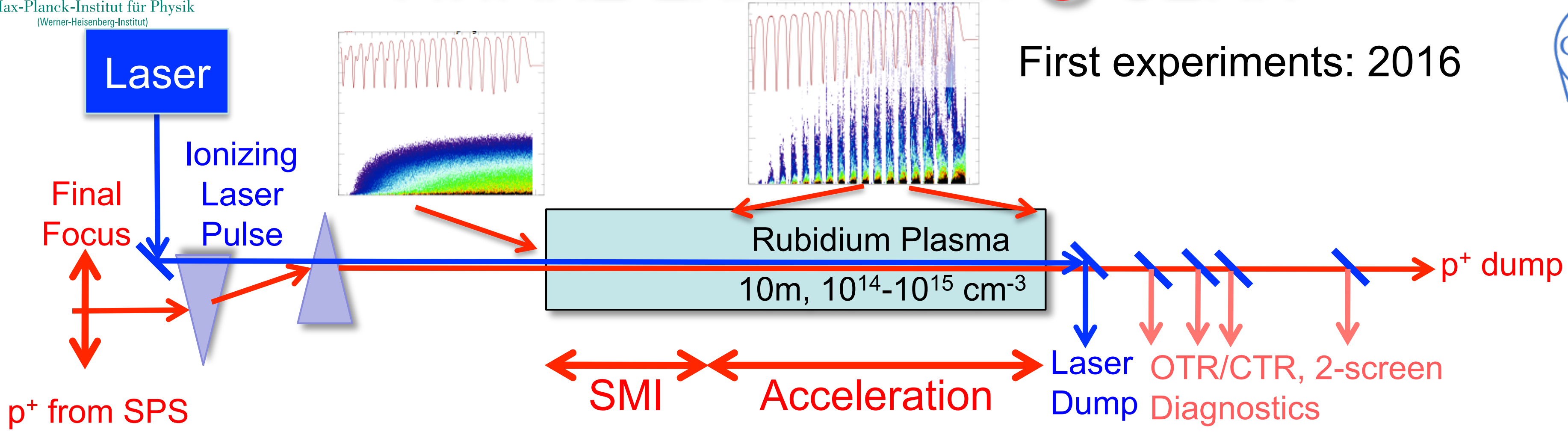
- ✧Short laser pulse creates the plasma and seeds the SMI
- ✧σ_z~12cm >> λ_{pe}~1.2mm (n_e~7x10^{14}cm^{-3}) => Self-modulation Instability (SMI)*
- ✧$\sigma_{z\ laser}$~30µm<<λ_{pe} => good seed

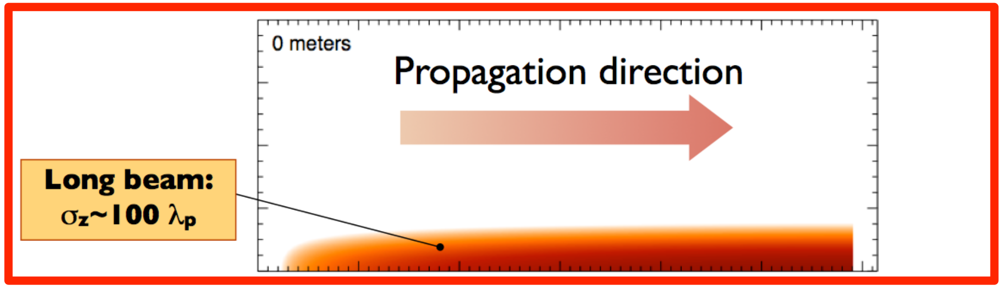
*Kumar, Phys. Rev. Lett. 104, 255003 (2010)

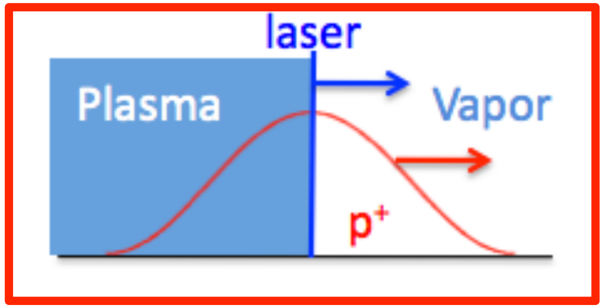
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

AWAKE EXPERIMENT @ CERN

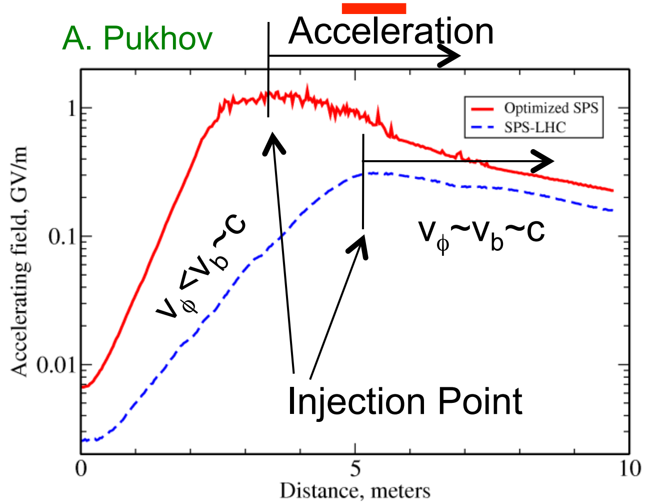
First experiments: 2016







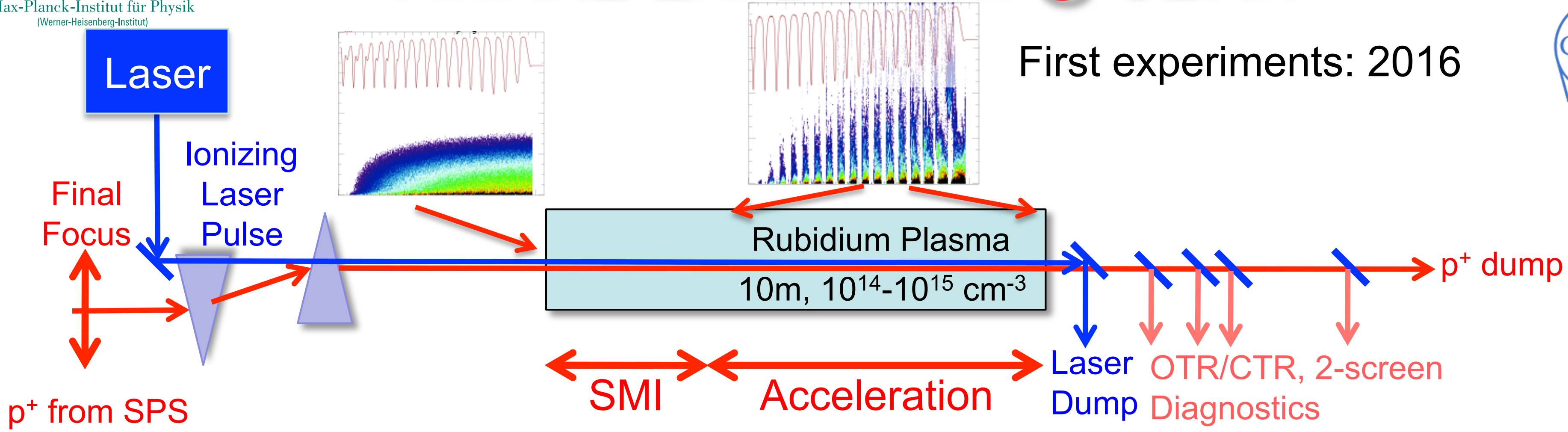
A. Pukhov

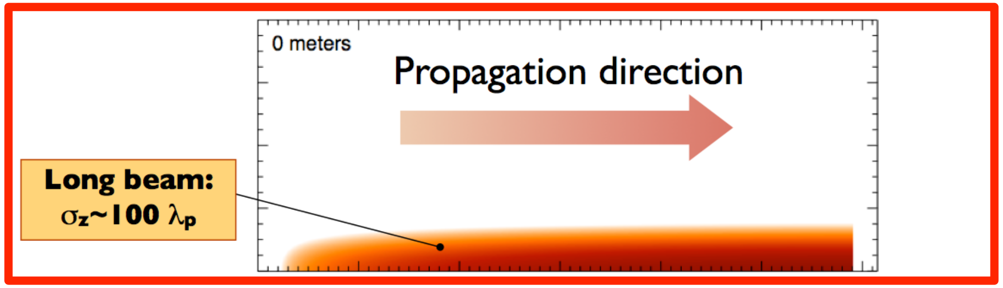


✧ The wakefields grow …

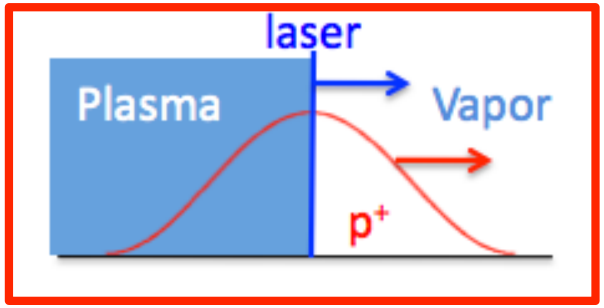
AWAKE EXPERiMENT @ CERN

First experiments: 2016

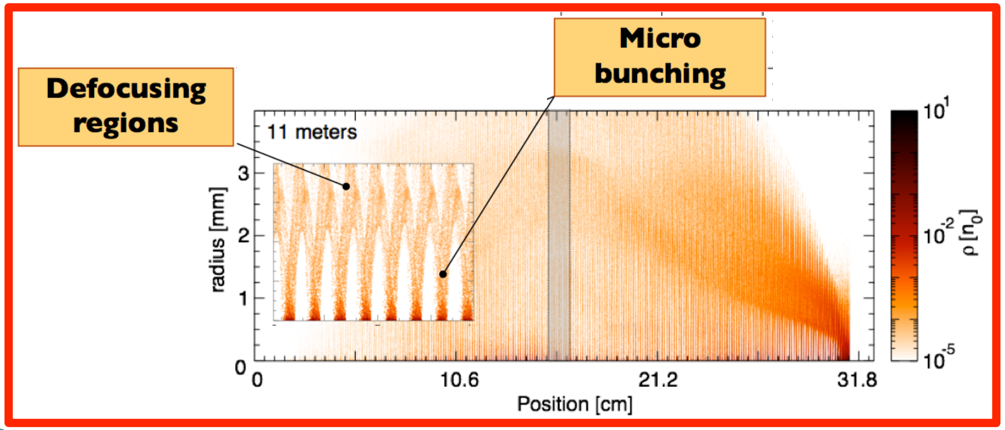




+



=



- The long (σ_z~12cm) p^+ bunch self-modulates with period λ_{pe}~1.2mm (n_e~7×10^{14}cm^{-3})
- ~100λ_{pe} per σ_z

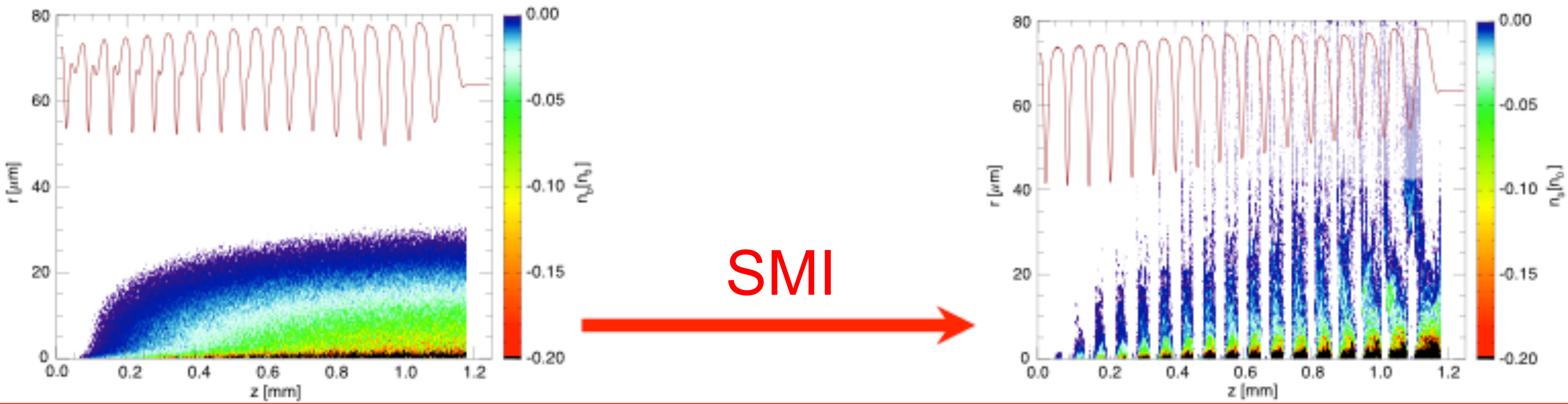
SMI DiAGNOSTiCS

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

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
$\sigma_z >> \lambda_{pe} \sim n_e^{-1/2}$

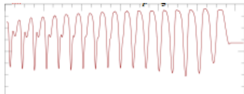


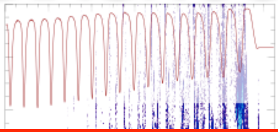
Mirror

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

SMI DiAGNOSTiCS

Laser





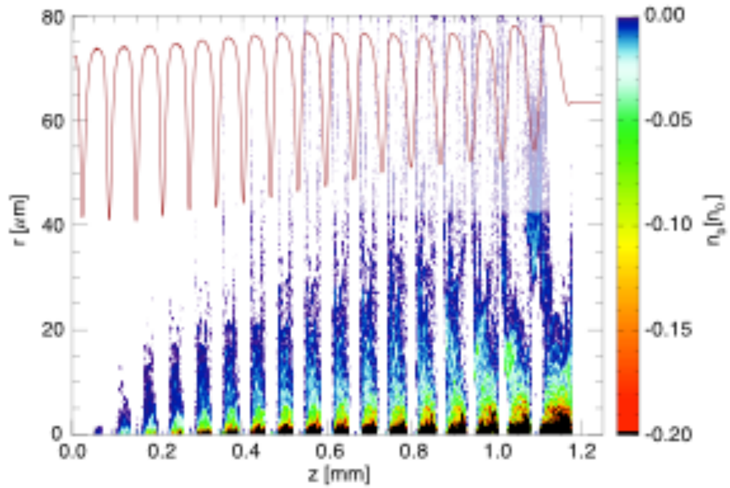
First experiments: 2016

1^{st} goal of AWAKE (2016-17):
demonstrate and study
the self-modulation instability (SMI)
of a long p^+ bunch in a dense plasma
$\sigma_z >> \lambda_{pe} \sim n_e^{-1/2}$

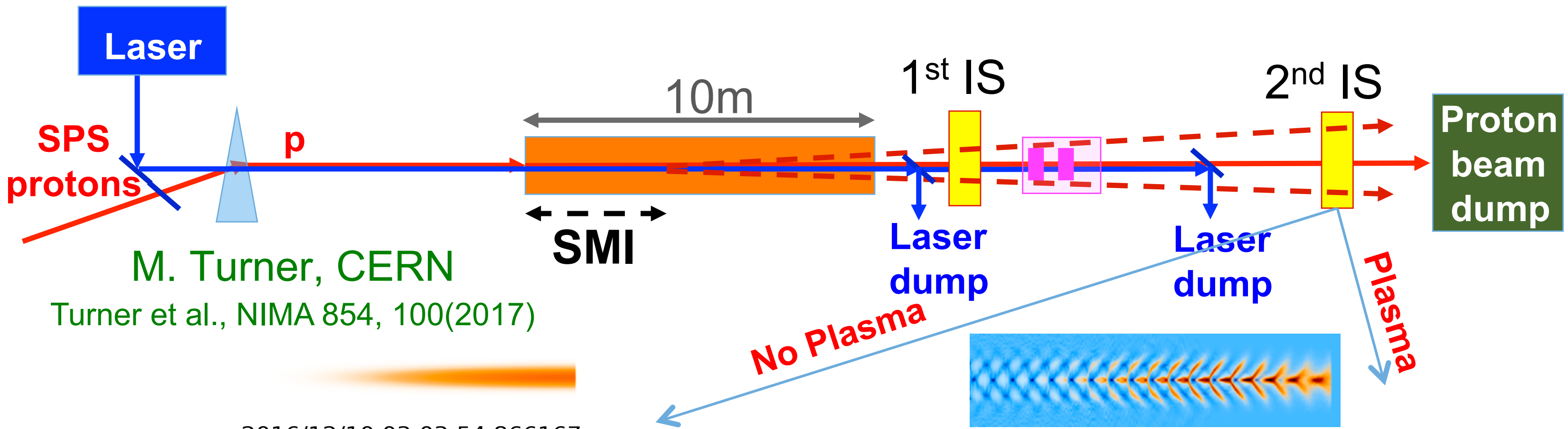
Three observables

- ✧ Defocused p^+
- ✧ p^+ bunch modulation at λ_{pe} (f_{pe})
- ✧ Emission of coherent transition radiation at λ_{pe} (f_{pe})

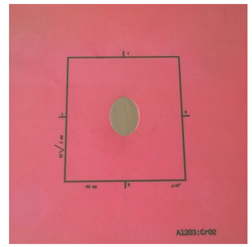
SMI →

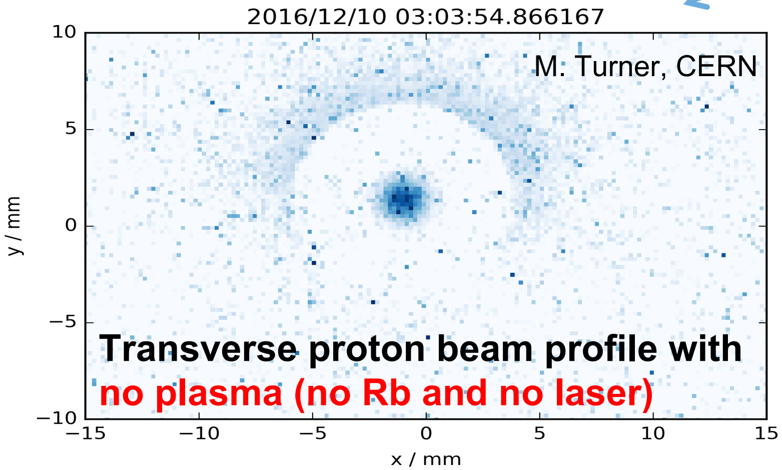


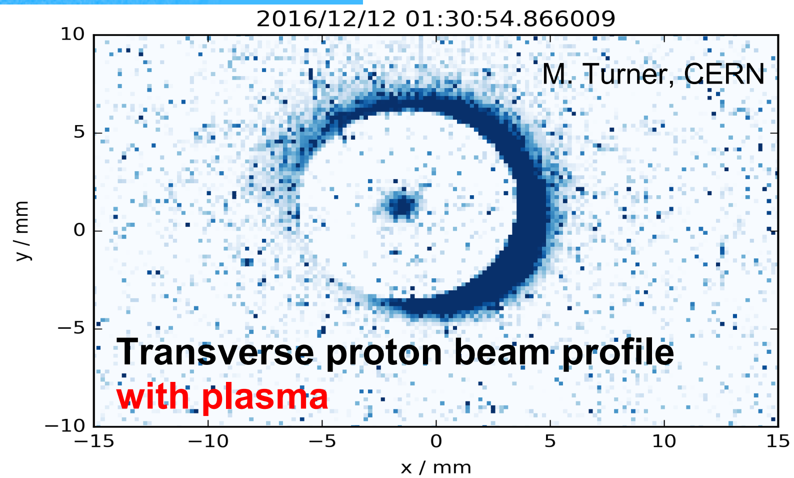
TWO-SCREEN SAMPLE RESULT



Screen



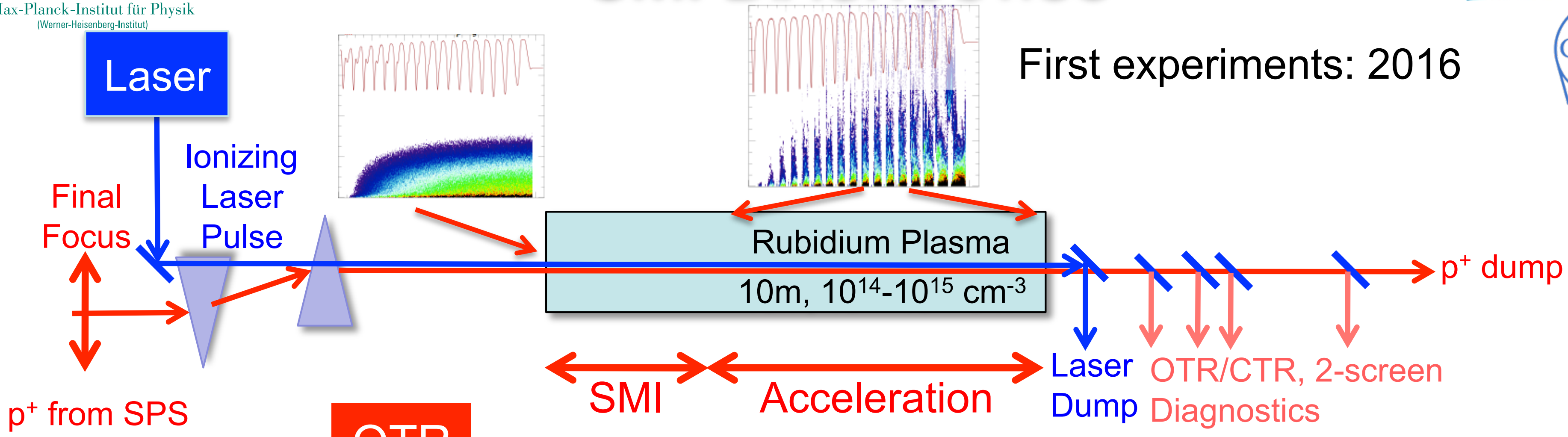


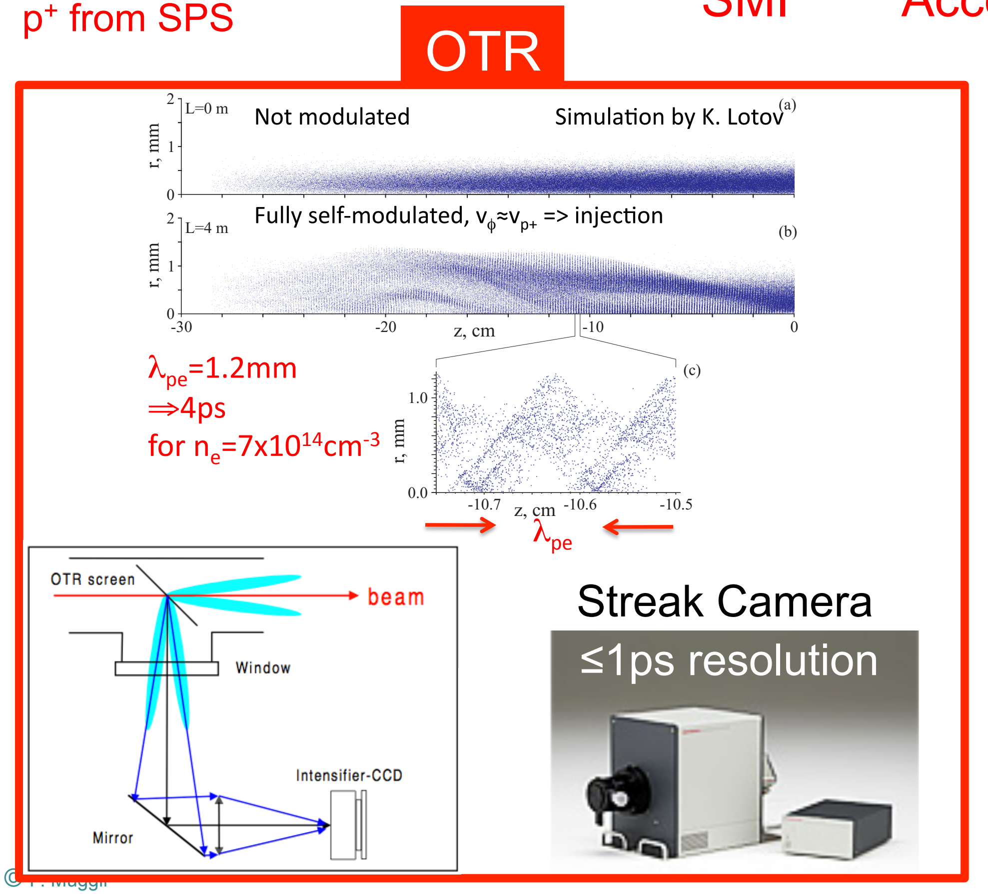


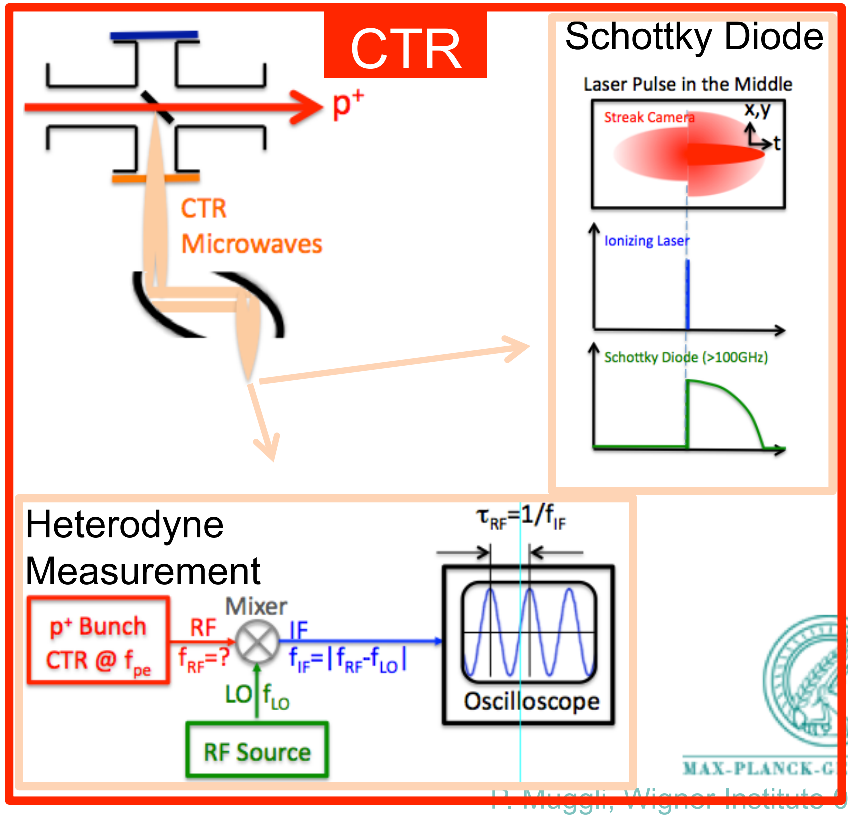
- ✧ p^+ defocused by the transverse wakefield (SMI) form a halo
- ✧ p^+ focused form a tighter core
- ✧ Estimate of the transverse wakefields amplitude ($\int W_{per} dr$)
- ✧ Information about saturation length?

SMI DiAGNOSTiCS

First experiments: 2016

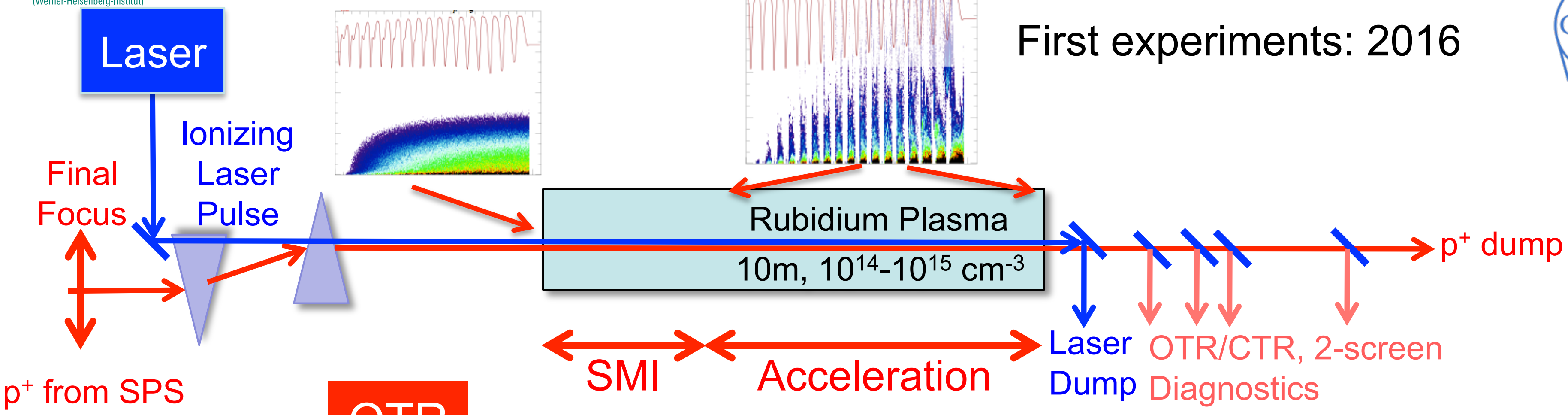


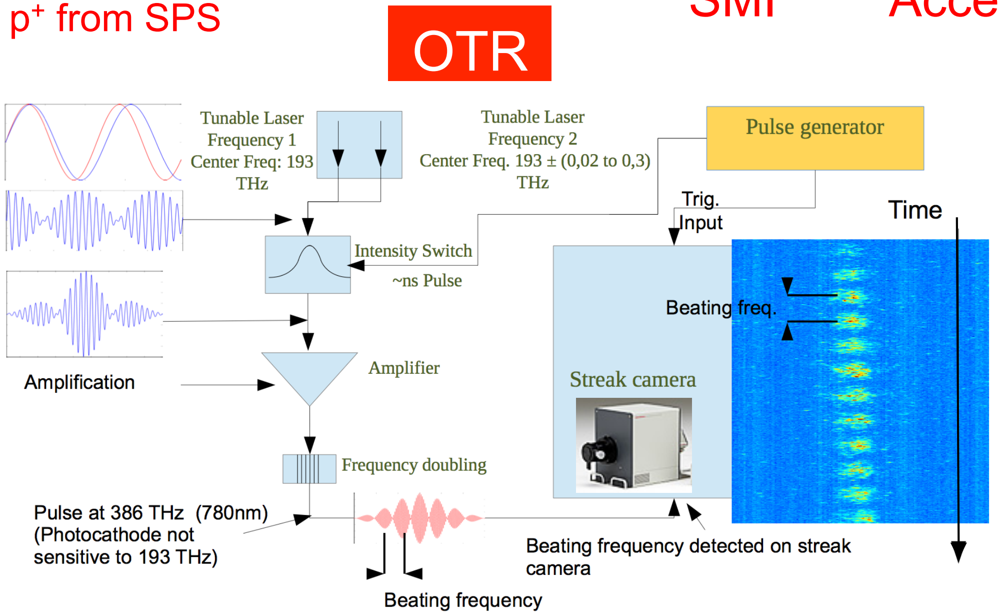




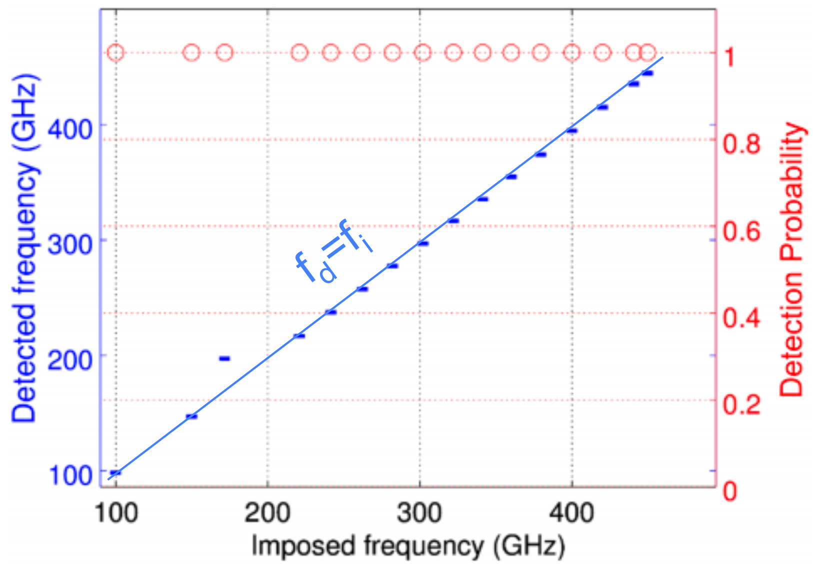
SMI DiAGNOSTiCS

First experiments: 2016





Rieger et al., Rev. Sci. Instr. 88, 025110 (2017)



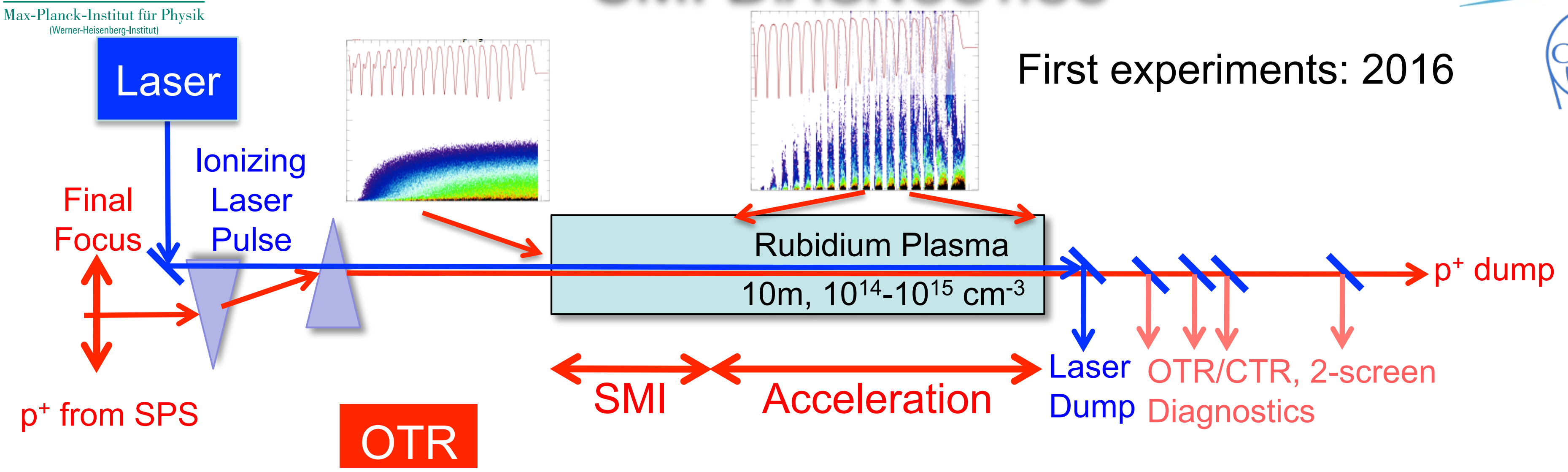
✧Emulate OTR light from self-modulated p^+ bunch with beating lasers

✧ps-modulation over ns time scale

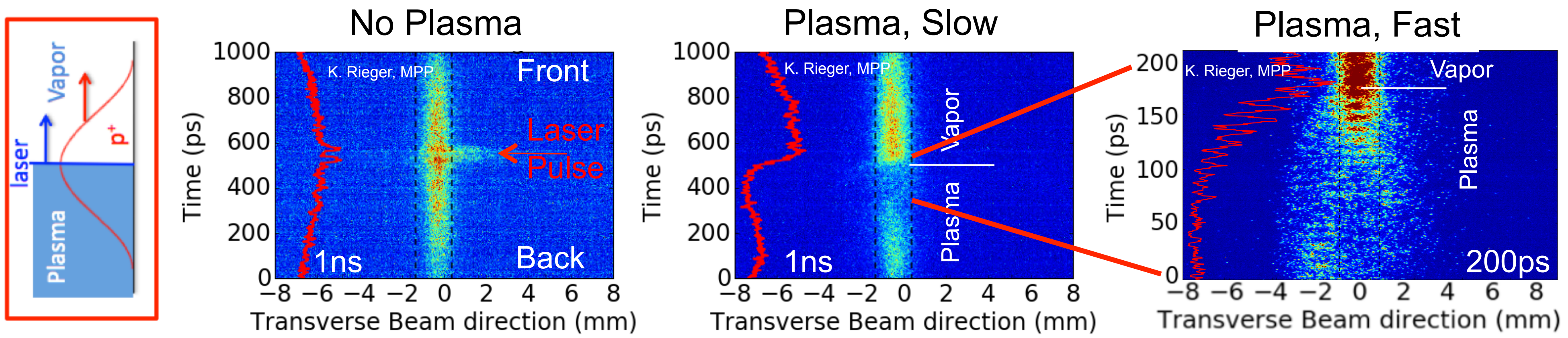
✧Measured frequency = "modulation" frequency

SMI DiAGNOSTiCS

First experiments: 2016



Streak camera Images

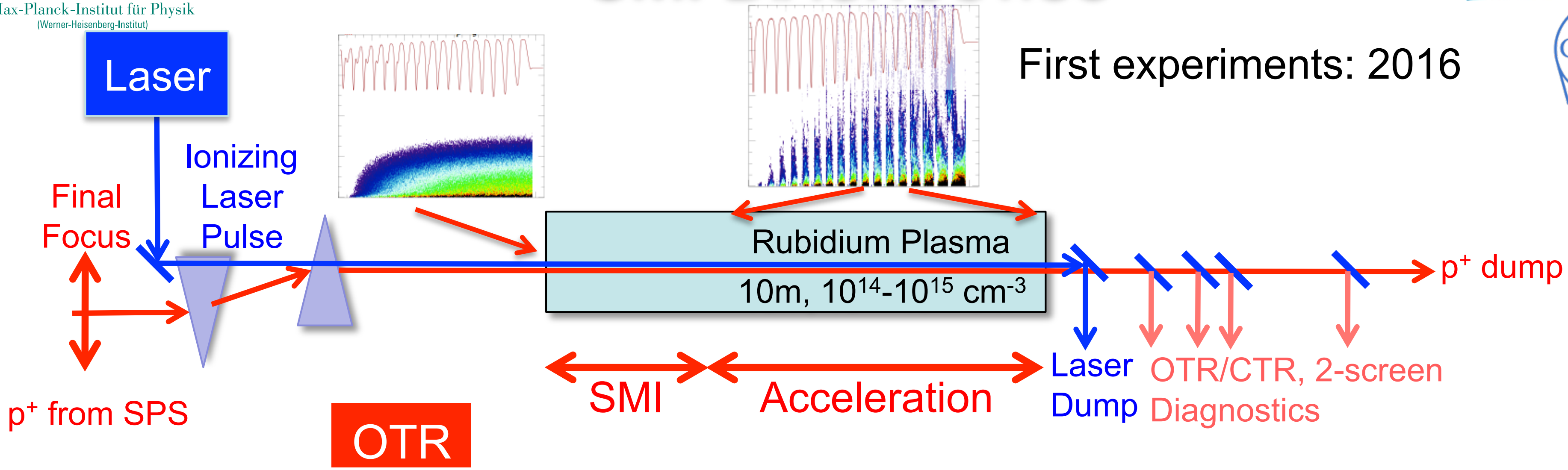


K. Rieger, MPP

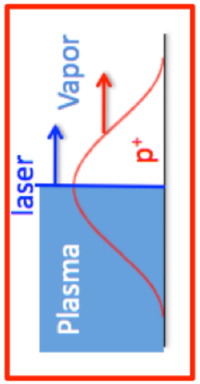
✧Timing at the ps scale
✧Effect starts at laser timing
✧Density modulation at the 10ps-scale visible

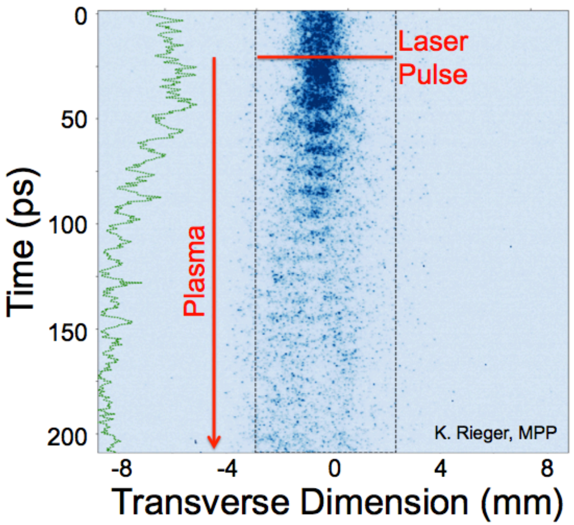
SMI DiAGNOSTiCS

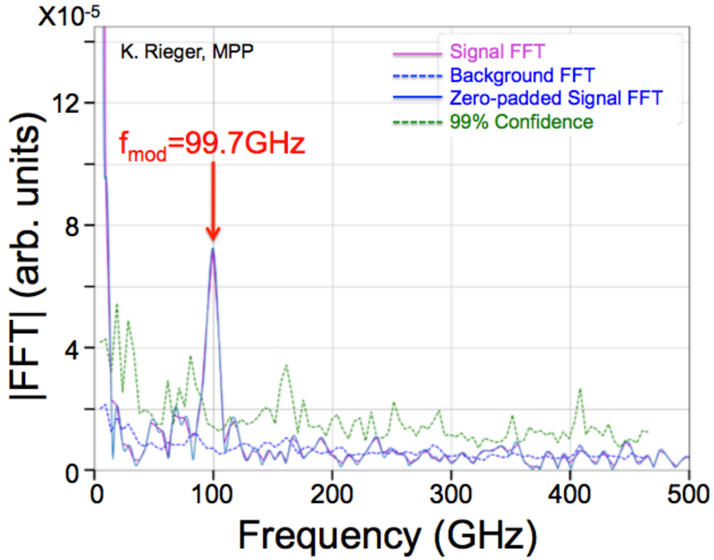
First experiments: 2016



Streak camera Image







✧$n_{Rb}=1.34\times10^{14}cm^{-3}$ => $f_{pe}=103.7GHz$

✧FFT peak at $f_{mod}=99.7GHz\sim f_{pe}$

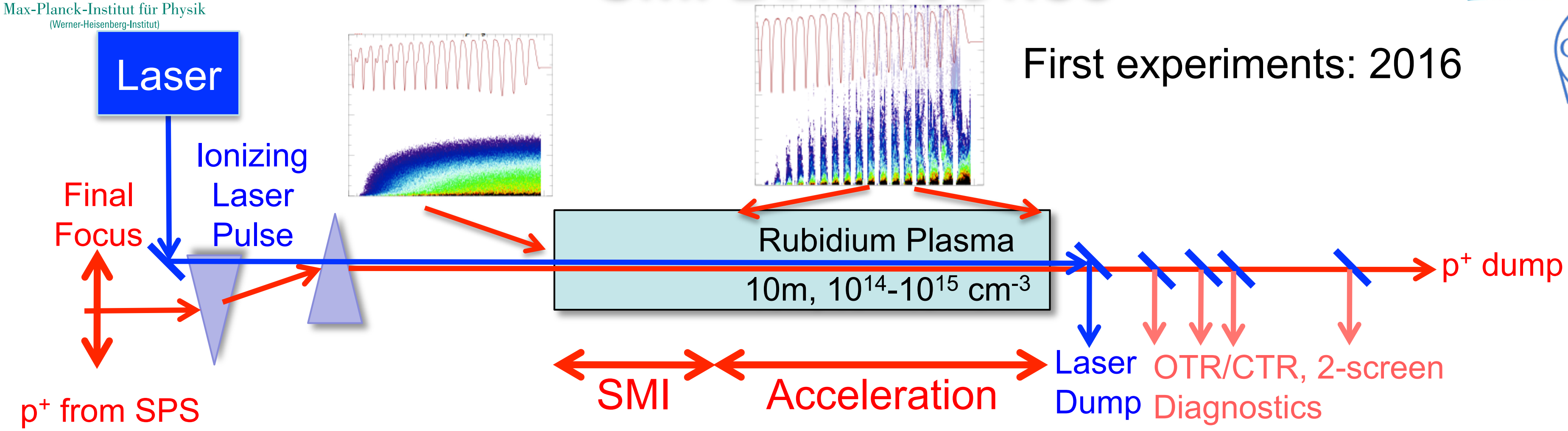
✧$\Delta f_{FFT}=4.5GHz$

K. Rieger, MPP

SMI DiAGNOSTiCS

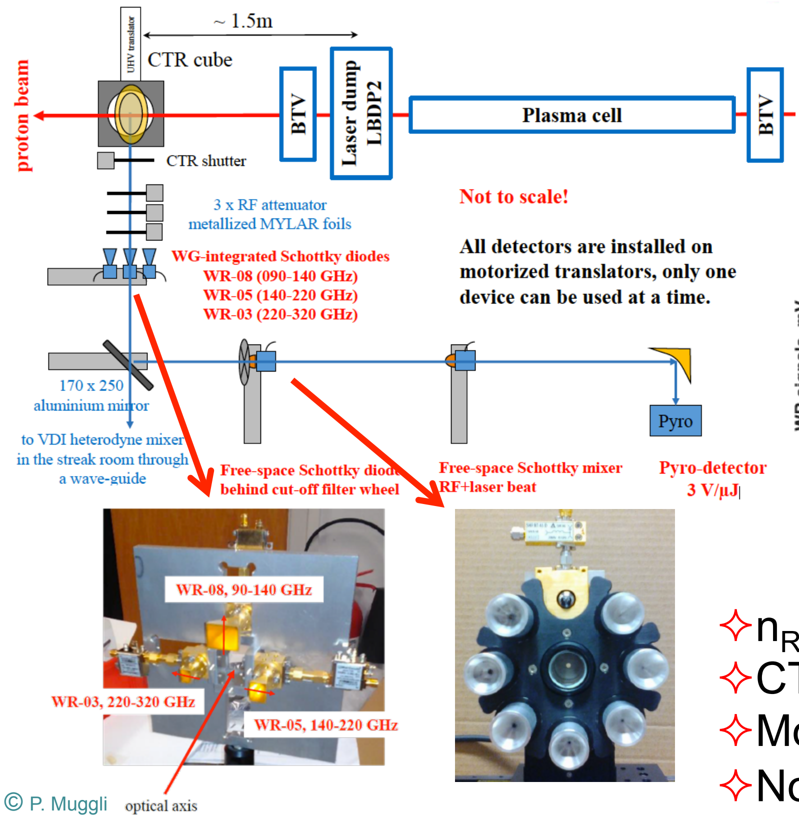
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

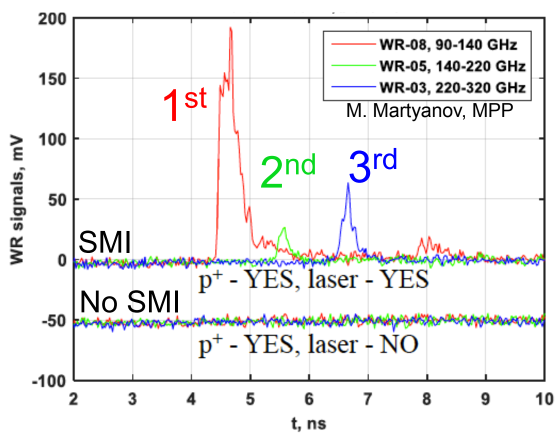
First experiments: 2016

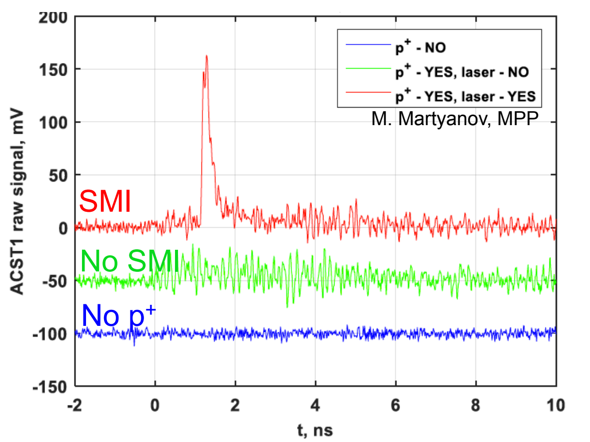


CTR

M. Martyanov,
F. Braunmueller, MPP



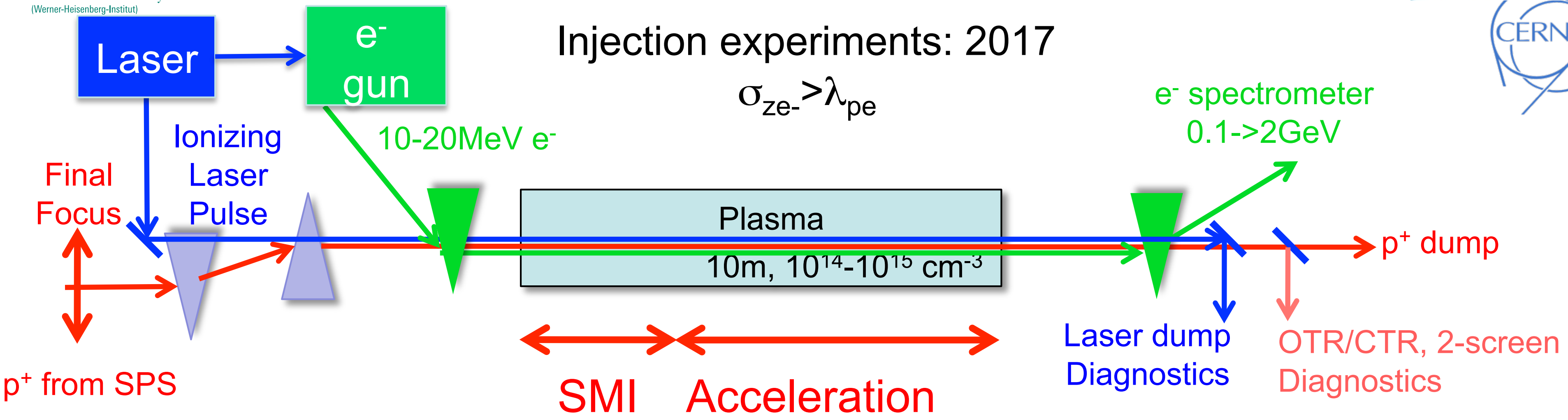


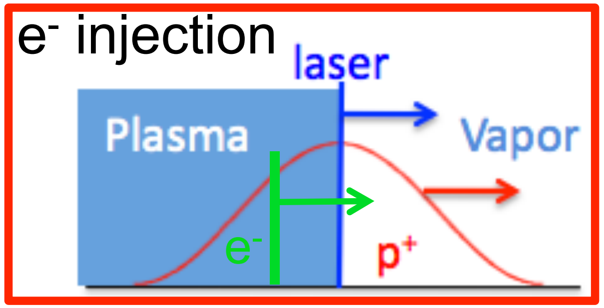


- ✧n_{Rb}~1.3x10^{14}cm^{-3} => f_{pe}~103GHz
- ✧CTR signal detected at harmonics (not calibrated)
- ✧Modulation is nonlinear
- ✧No frequency measurement

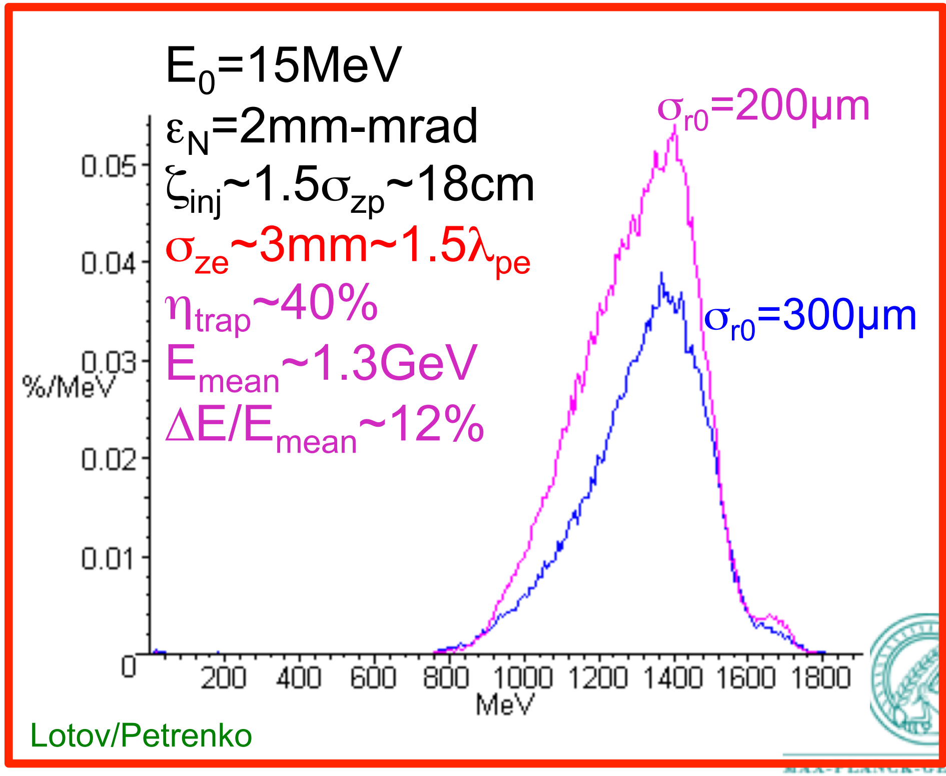
MAX-PLANCK-GESELLSCHAFT

WAKEFIELDS SAMPLING / ACCELERATION

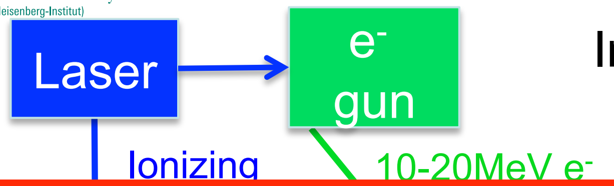




✧ Accelerate e⁻ to multi-GeV energies with ~GeV/m gradient



WAKEFiELDS SAMPLiNG / ACCELERATiON



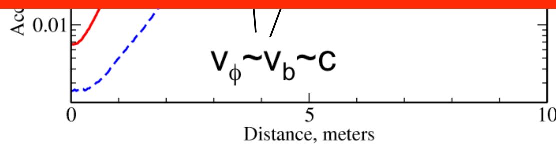
Injection experiments: 2017

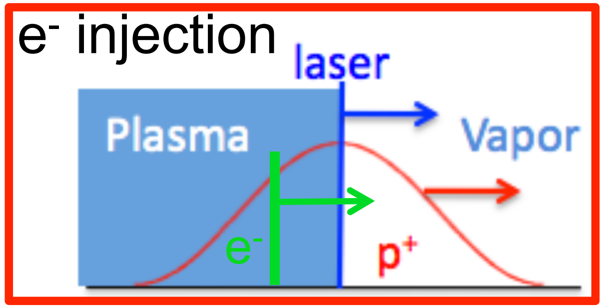
$\sigma_{ze-} > \lambda_{pe}$

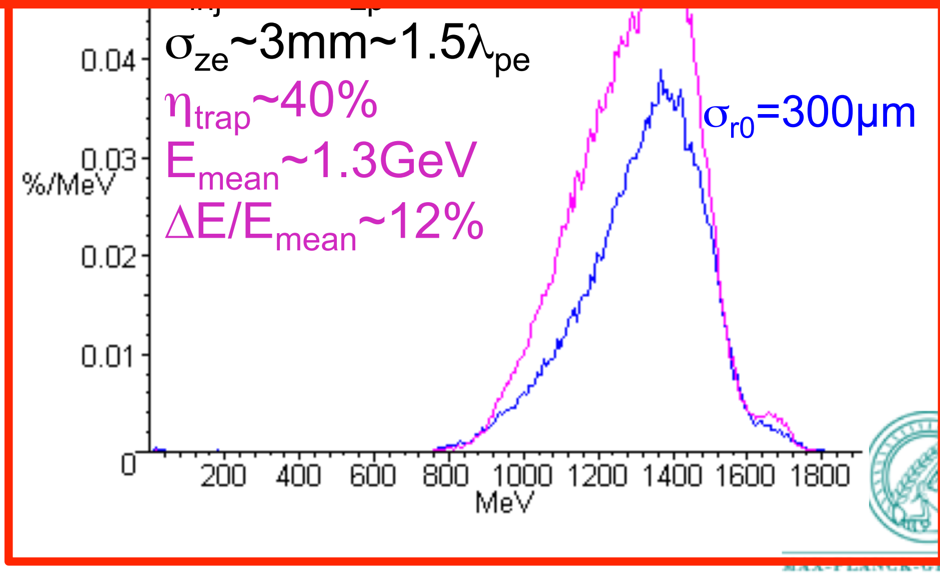
EOS

e^- spectrometer
0.1->2GeV

2^{nd} goal of AWAKE (2017-18):
Externally inject (~15MeV) electrons
into the wakefields
and
reach ~GeV energy gain with narrow ΔE/E

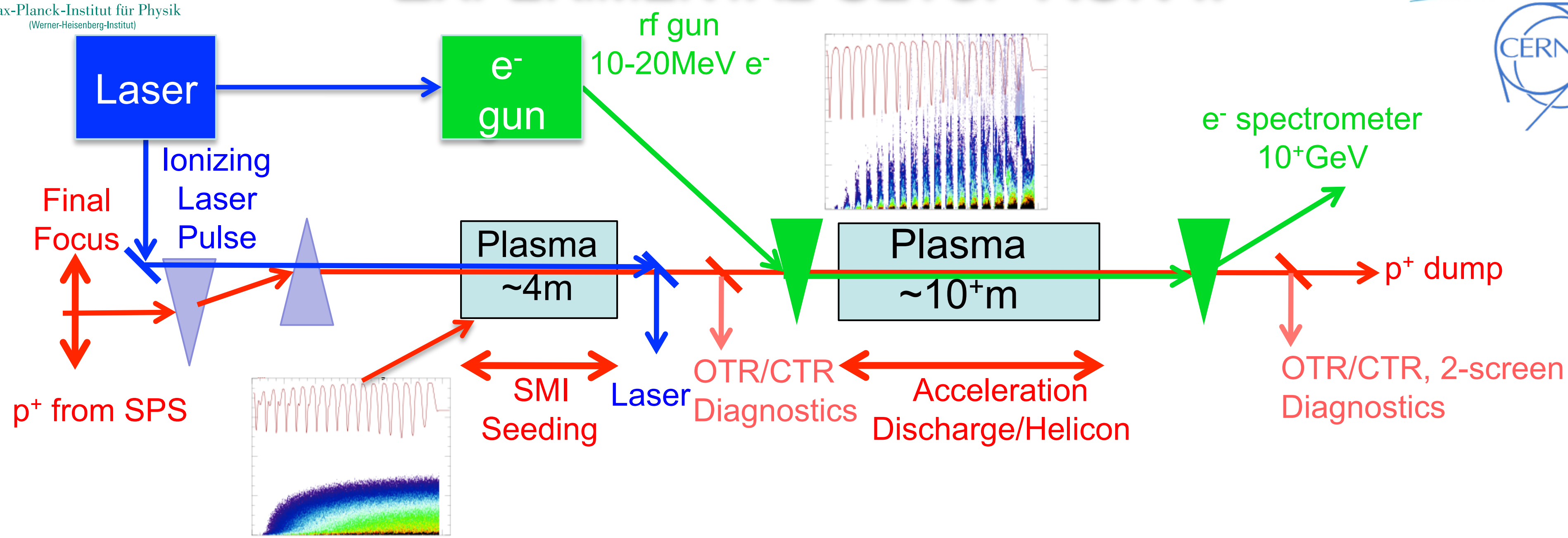


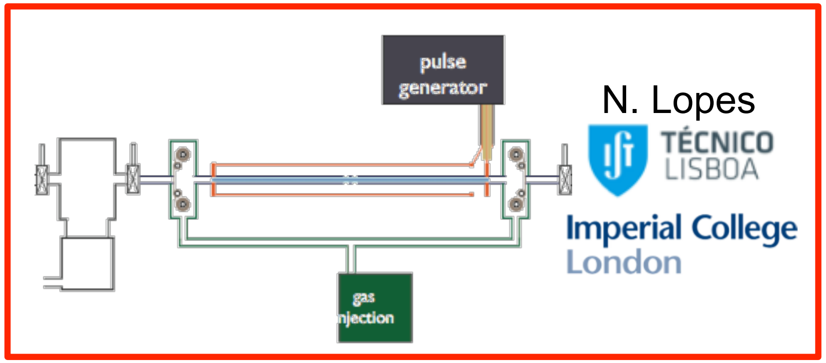


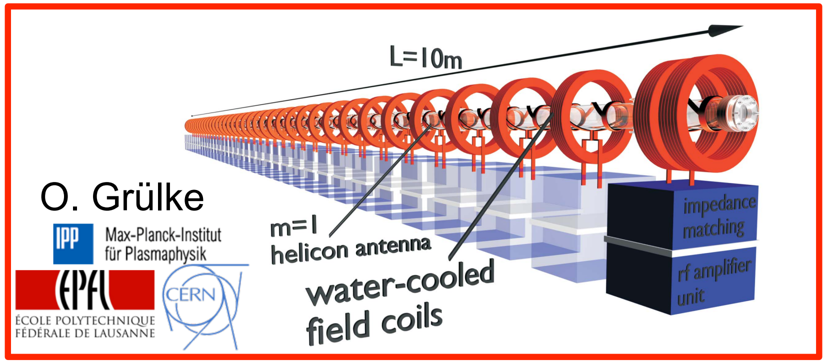


✧ Accelerate e^- to multi-GeV energies with ~GeV/m gradient

ExperiMental Setup RUN II







- ✧ 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 ($\sigma_z << \lambda_{pe}$), quality of the bunch ($\Delta E/E$, ε)
- ✧Density step to maintain accelerating gradient

✧2021-LS3, **RUN II**

SUMMARY

- 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 ($\Delta E/E$, 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
- Ionization seems to occur even at high n_{Rb} … (good for AWAKE)
- Can we get some interesting physics from laser propagation/ionization? Unique tools for non-linear optics? Rb, well controlled and diagnosed …

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

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

SUMMARY

AWAKE
CERN

2nd Wigner/MPP AWAKE workshop: Laser plasma generation for particle acceleration
Wigner Research Centre for Physics, Budapest 2017. May 05.

Program
9:15-9:30. Gagik Djotyan. Introductory remarks
9:30-9:45. Péter Lévai: Wigner Research Center: Research directions
9:45-10:15. Patric Muggli: Summary of the first SMI results of AWAKE
10:15-10:45: Coffee break
10:45-11:15. Béla Ráczkevi: Laser plasma diagnostics in rubidium vapor cell
11:15-11:45. Josh Moody: First Full Scale Laser Propagation Results Through the 10 Meter Rb Vapor Source at AWAKE
11:45-12:15. Chen Lin: Recent progress of Compact laser plasma Accelerator (CLAPA) at Peking University
12:15-12:45. Anna-Maria Bachmann. Laser plasma radius measurement.
12:45-13:45. Lunch
13:45-14.30. Visit to the Wigner Laser Lab (Miklós Kedves)
14:30-15:00. Gábor Demeter: Modeling the interaction of ionizing laser pulses with rubidium atoms for the AWAKE project
15:00-15:30. Andrea Armaroli: Efforts for modeling dispersive non-linear polarizability
15:30-16:00. Mikhail Martyanov: Ionization diagnotistic
16:00-16:30. Coffee break
16:30-17:00. Fabian Batsch: Interferometer-based white light measurement of neutral rubidium density and gradient at AWAKE
17:00 - 17:30. Mathias Hüther: "Concept of SMI-seeding with an electron bunch.
17:30- 18:00. Mihály Pocsai: Ionization of rubidium with ultrashort intense laser pulses
18:00-18:45. Round table discussions
Dinner: 19.15-22.15

MAX-PLANCK-GESELLSCHAFT

Thank you to my collaborators

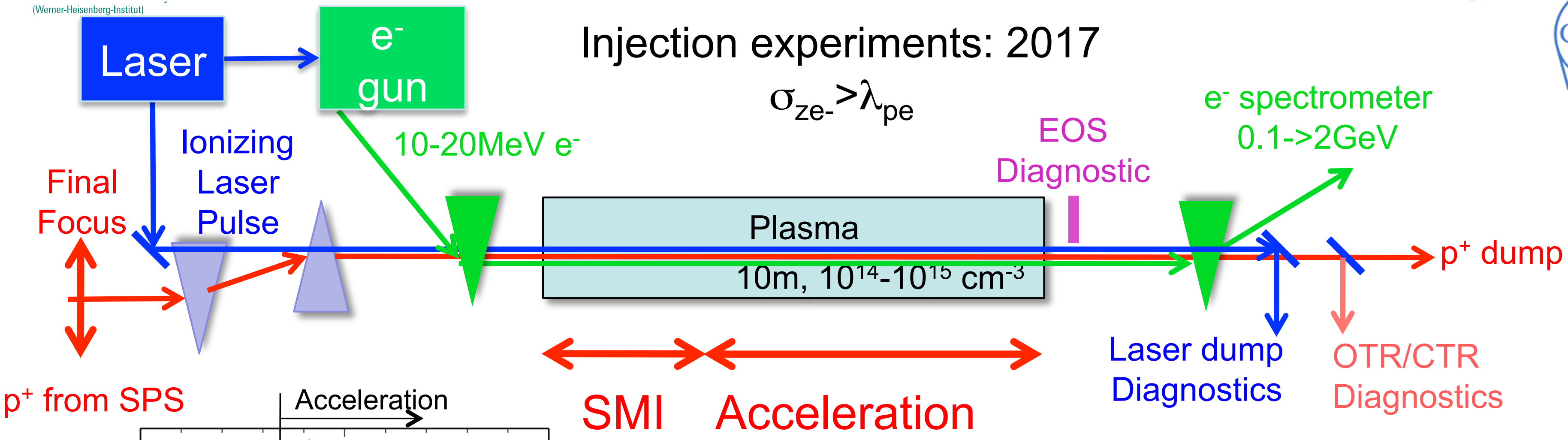
Thank you!

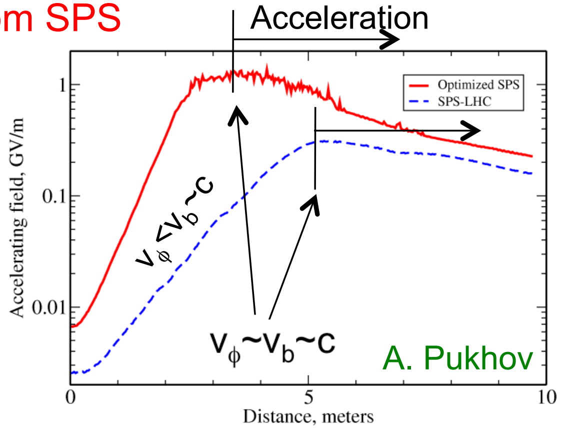
http://www.mpp.mpg.de/~muggli
muggli@mpp.mpg.de

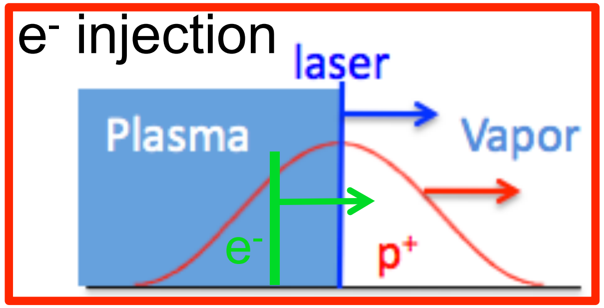
WAKEFiELDS SAMPLiNG / ACCELERATiON

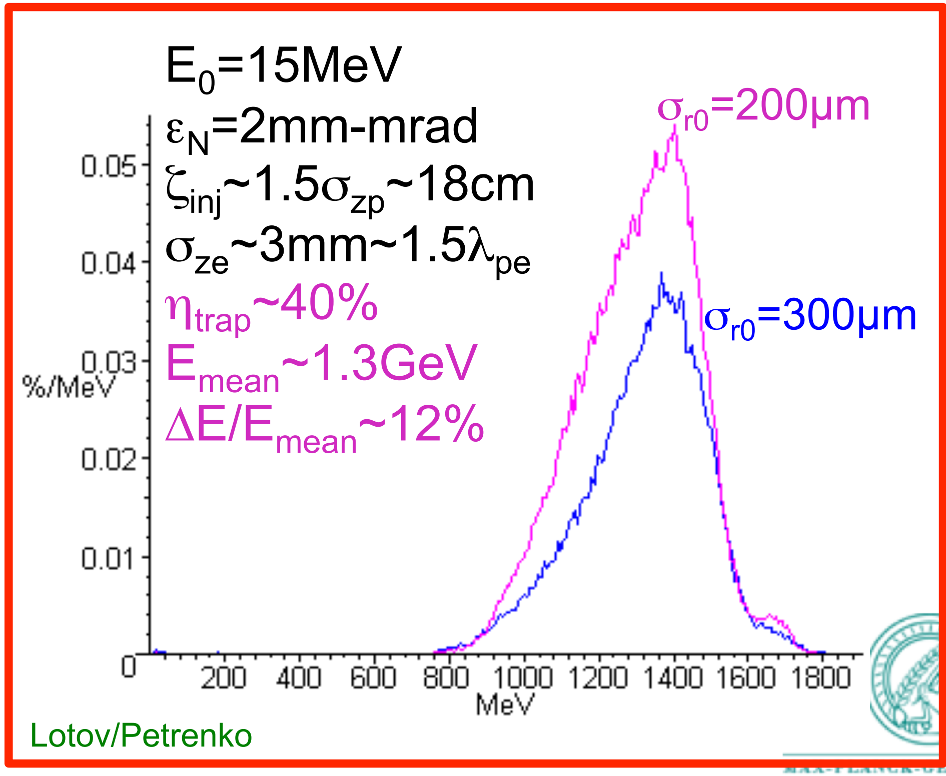
Injection experiments: 2017

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





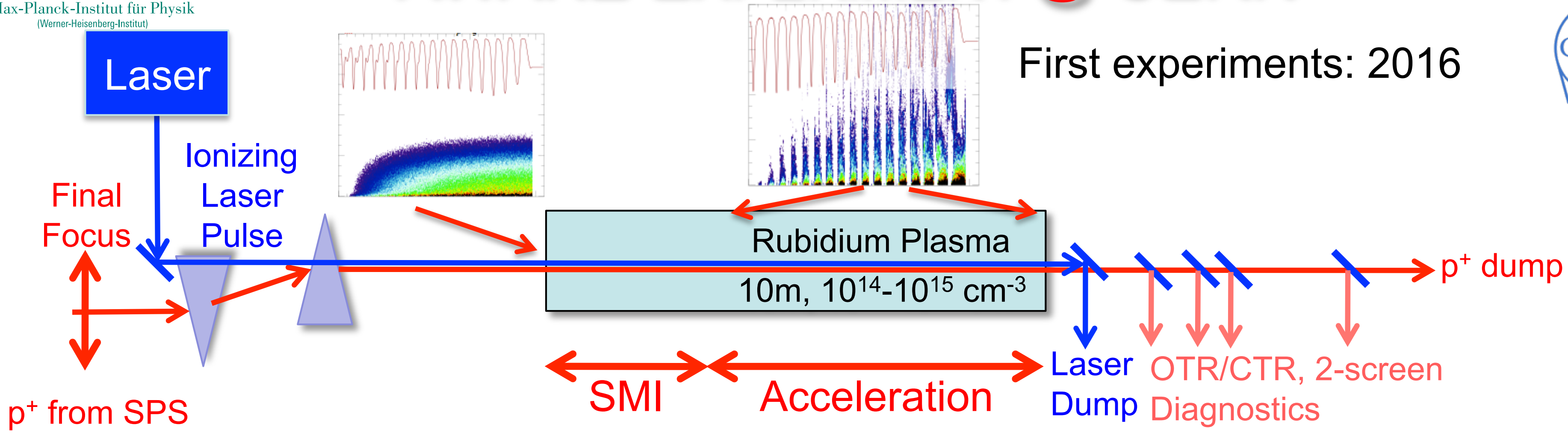


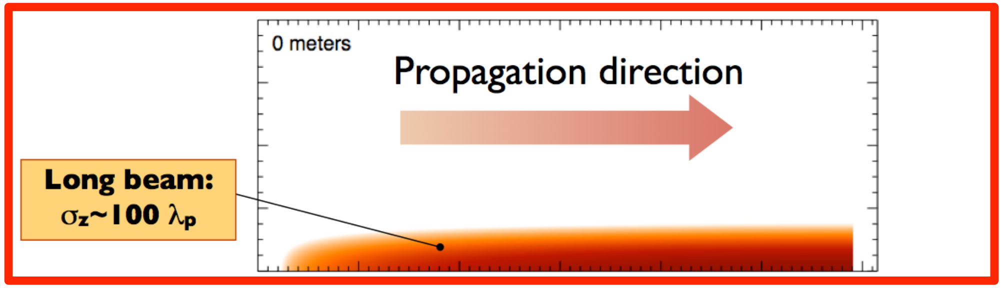


✧ Accelerate e- to multi-GeV energies with ~GeV/m gradient

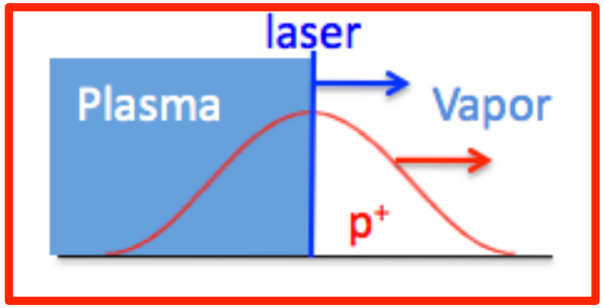
AWAKE EXPERiMENT @ CERN

First experiments: 2016

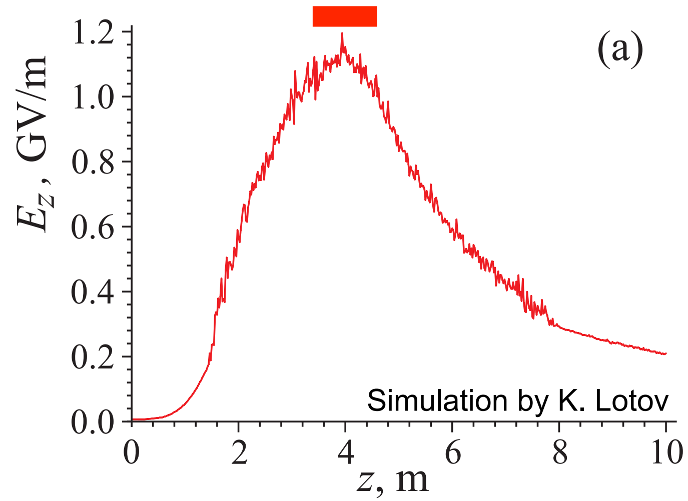




+

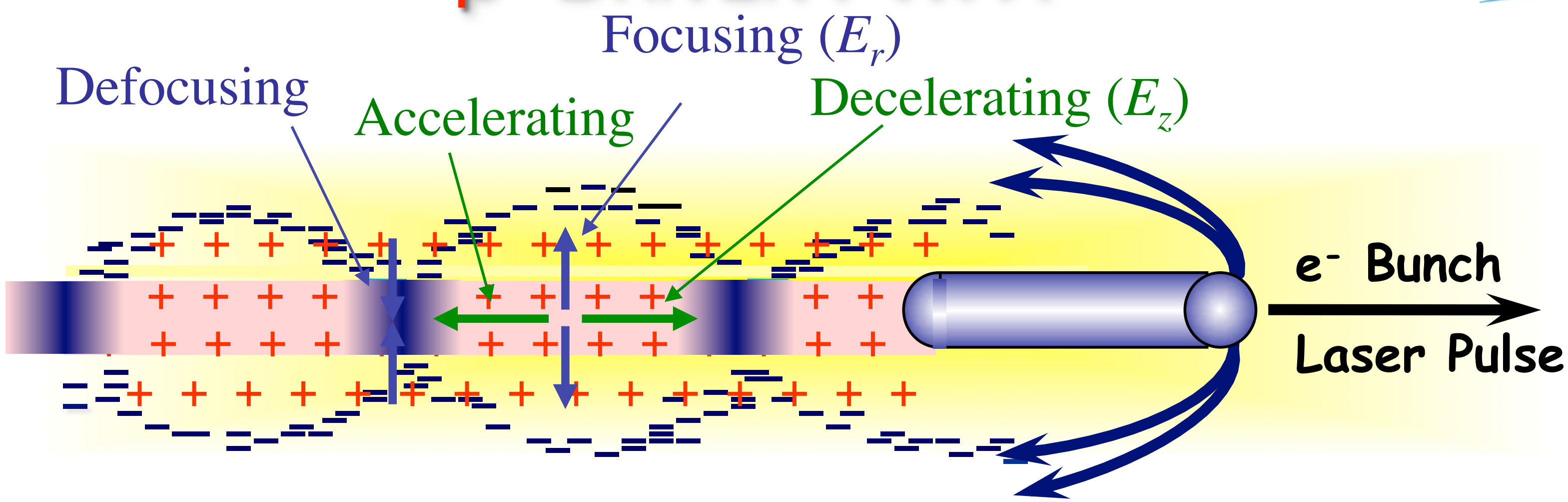


=



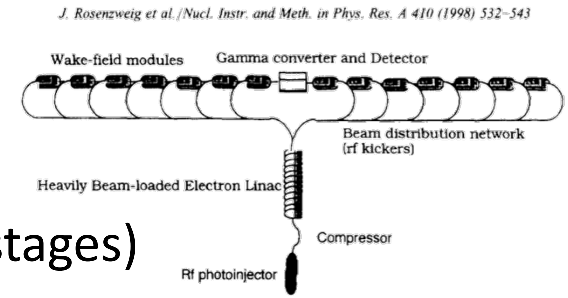
✧ The wakefields grow …

p⁺-DRiVEN PWFA



✧ILC-CLIC, 0.5TeV bunch with $2\times10^{10}e^-$ ~1.6kJ

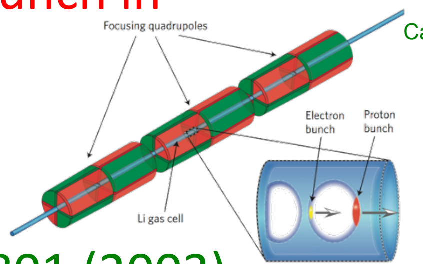
✧SLAC, 20GeV bunch with $2\times10^{10}e^-$ ~60J



✧SLAC-like driver for staging (FACET= 1 stage, collider 10^+ stages)

✧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!



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

✧Large <u>average</u> gradient! (≥1GeV/m, 100's m)

✧Wakefields driven by e^+ bunch: Blue, PRL 90, 214801 (2003)