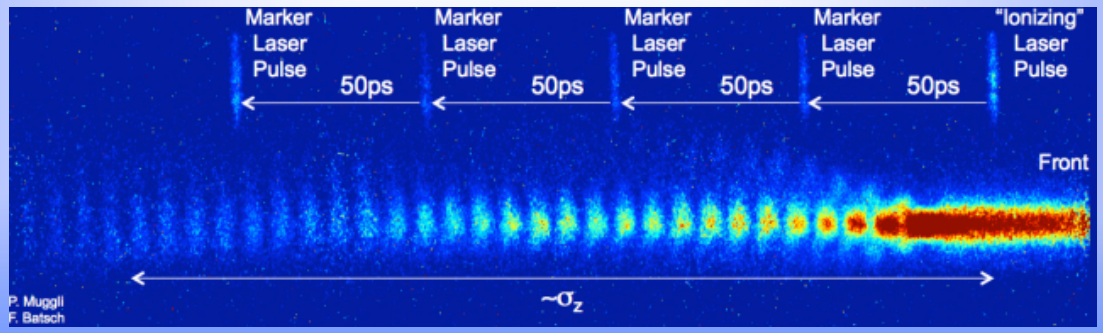
The proton driven advanced wake field acceleration experiment (AWAKE) at CERN

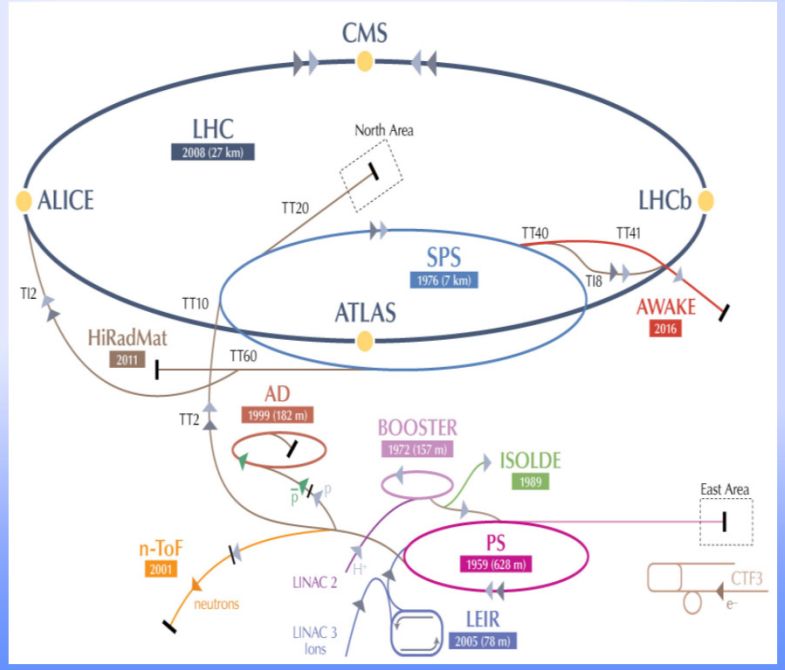
Steffen Doebert
On behalf of the AWAKE collaboration



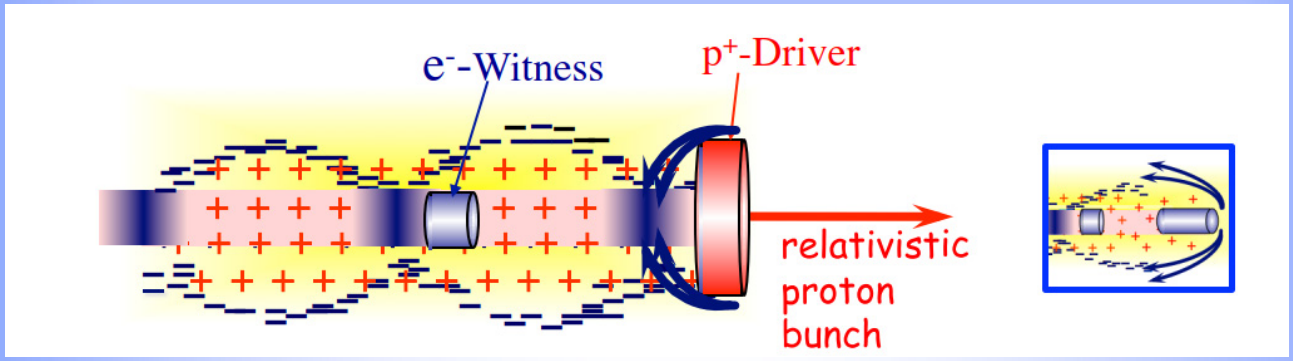
- The AWAKE experiment
- Seeded self modulation of a long proton bunch
- First electron acceleration results
- Conclusion and Outlook

Advanced WAKefield Experiment

- Demonstration of proton driven plasma wakefield acceleration
- GV/m gradients for acceleration
- Application for high energy physics



Proton driven plasma wakefield acceleration



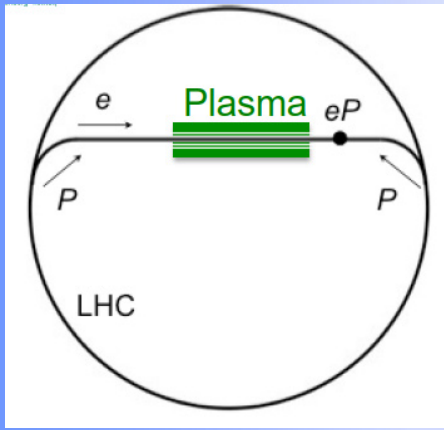
A proton bunch carries much more energy then an electron bunch or laser pulse

❑ PW laser, 1 PW, 10 fs	~10 J
❑ SLAC, 42 GeV, 2×10^{10} e^-	~ 130J
❑ ILC, 0.5 TeV, 2×10^{10} e^-	~1.6 kJ
❑ SPS, 400 GeV, 3×10^{11} p^+	~19 kJ
❑ LHC, 7 TeV, 10^{11} p^+	~112 kJ

→ A single SPS or LHC bunch could accelerate electron to the TeV range in a single stage ! Large average gradient >1 GV/m

→ No need for multi stages like in electron driven or laser driven PWA

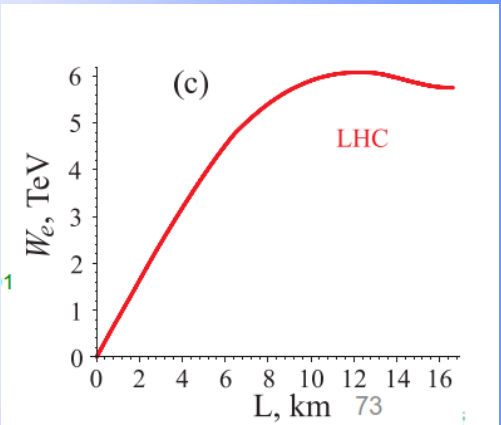
Possible applications
Proton driven PWFA for e^-/p^+ collider



Luminosity using typical LHC parameters

$L = f \cdot N_e \cdot N_p / 4\pi\sigma_x\sigma_y \sim 5 \cdot 10^{28}\ cm^{-2}s^{-1}$

7 TeV protons / 3 TeV electrons



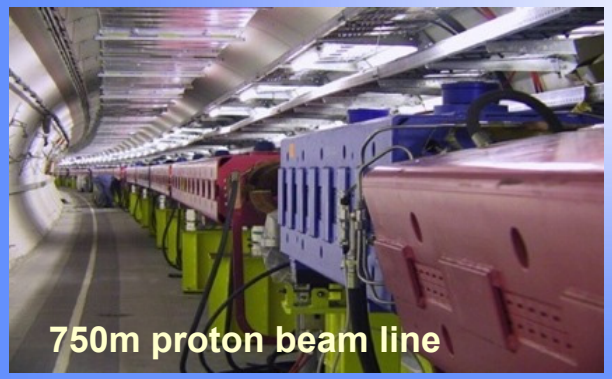
Possible applications:

- **Fixed target or beam dump experiments at 10s of GeV**
- **LHeC like collider using SPS as driver, 70 GeV electrons**
- **e^-/p^+ using LHC as driver, TeV electrons**

VHEeP: A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463

Suitable proton driver for plasma wakefield acceleration

Parameter	Protons
Momentum [MeV/c]	400 000
Momentum spread [%]	±0.035
Particles per bunch	$3 \cdot 10^{11}$
Charge per bunch [nC]	48
Bunch length [mm]	120 (0.4 ns)
Norm. emittance [mm·mrad]	3.5
Repetition rate [Hz]	0.033
1σ spot size at focal point [μm]	200 ±20
β-function at focal point [m]	5
Dispersion at focal point [m]	0



Plasma frequency: $\omega_p = (4\pi n_0 e^2/m_e)^{-1/2}$

Plasma wavelength: $\lambda_p = 2\pi c/\omega_p$.

Wake amplitude: $E_{WB} = m_e c\omega_p/e = m_e c^2/e\sigma_z$

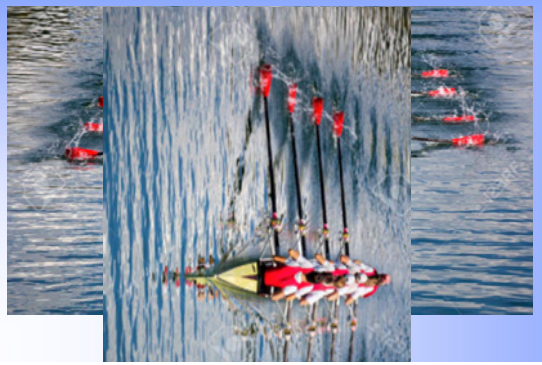
In Awake: $n_o = 7 \cdot 10^{14}$ cm^{-3} , $\lambda_p = 1.2$ mm

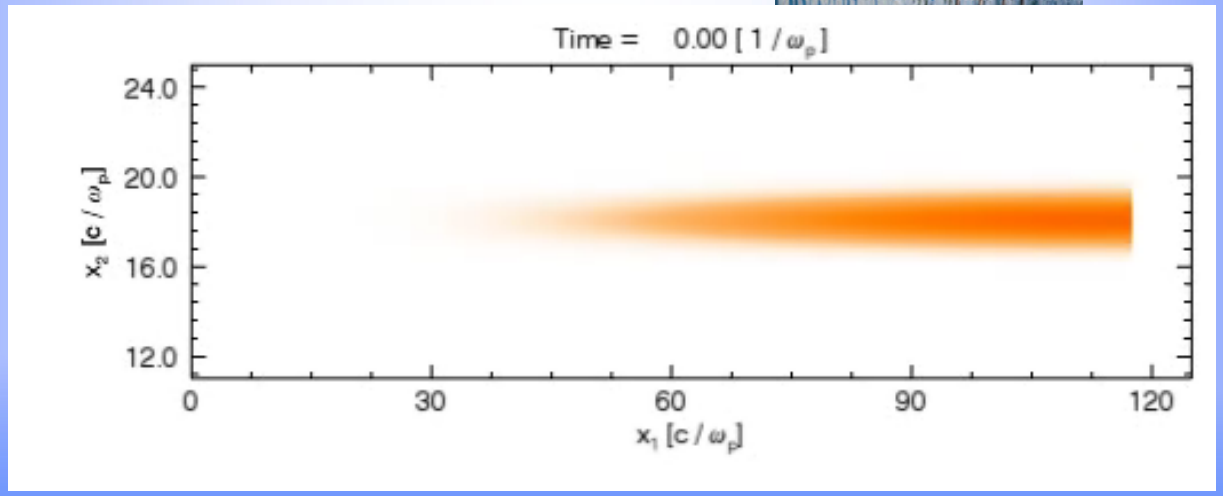
To drive wake efficiently driver bunch length need to be < λ_p

For example for σ_z ~1 mm we get E_{WB} ~ 1 GV/m

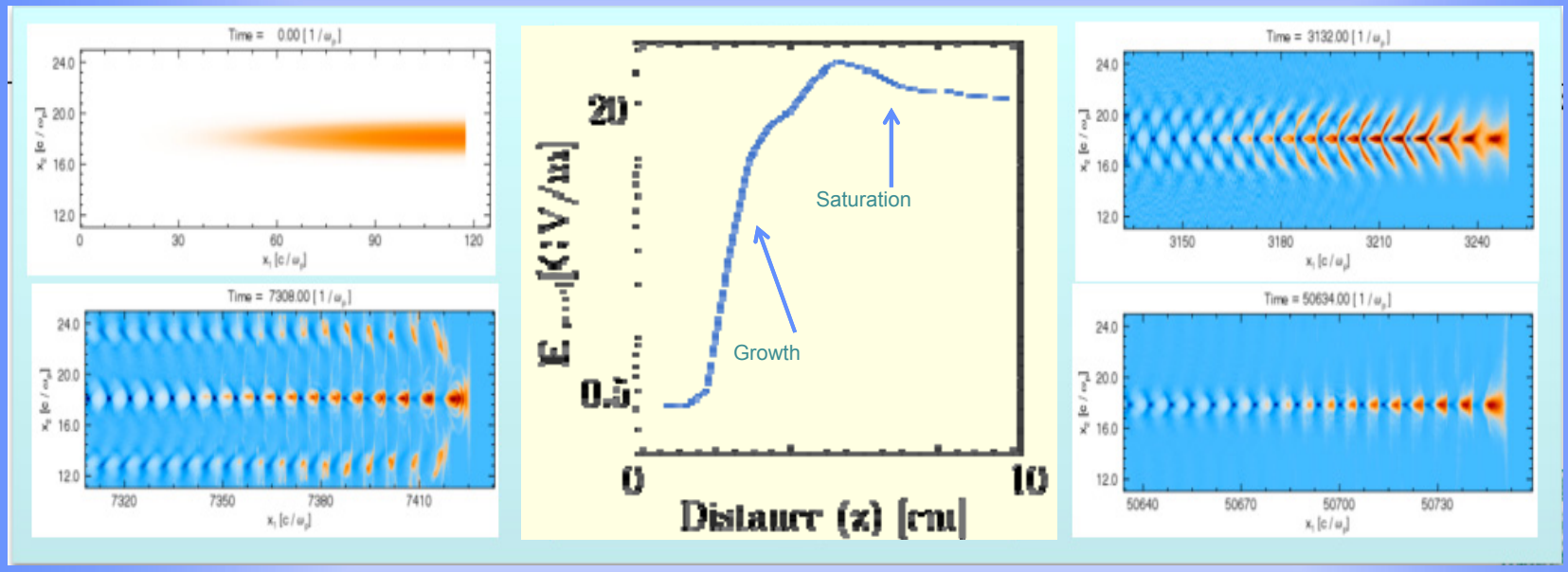
→ Profit from transverse wake field to initiate self modulation leading to micro bunching at the scale of the plasma wavelength which drives the longitudinal wake field resonantly

Seeded Self Modulation (SSM)



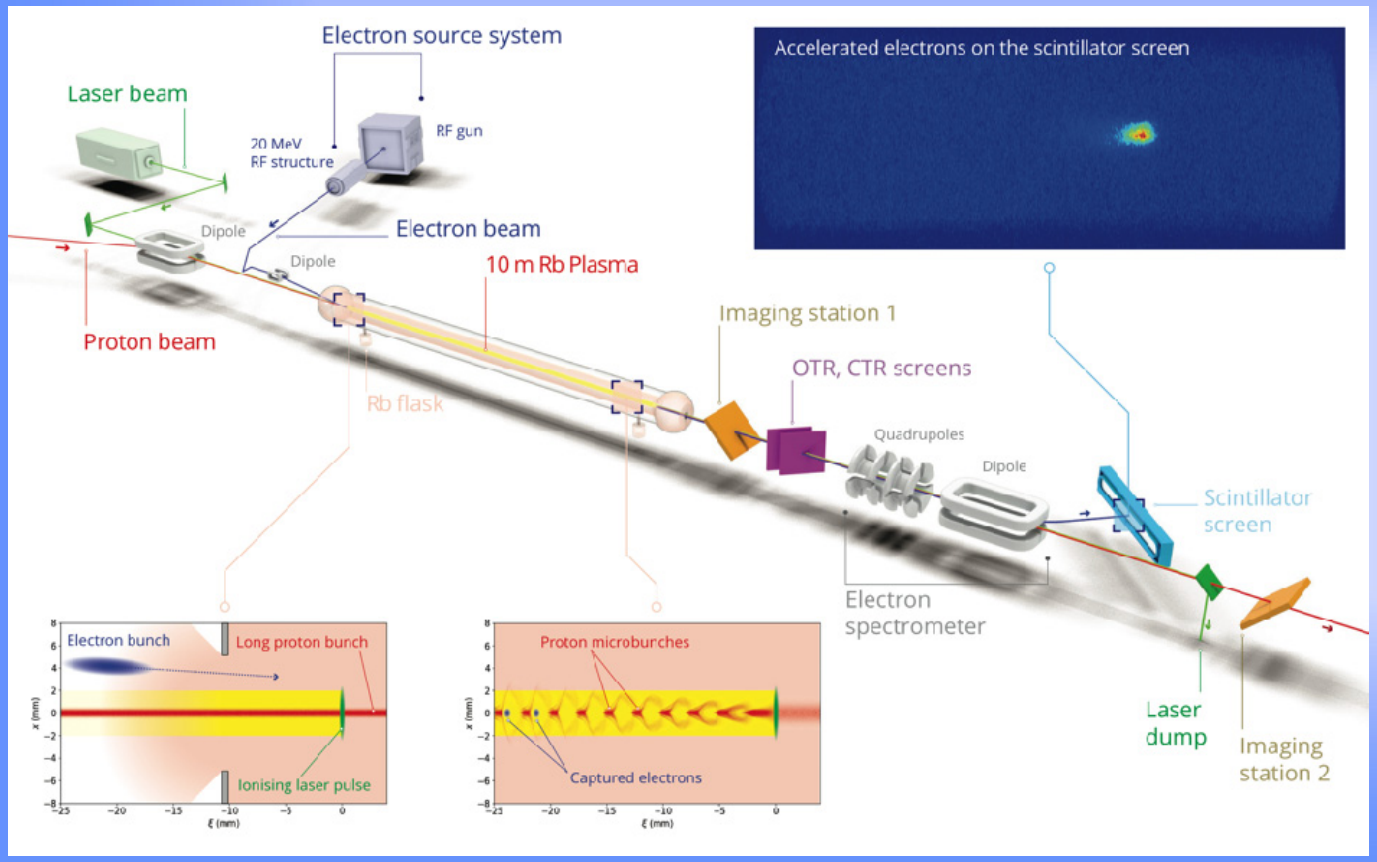


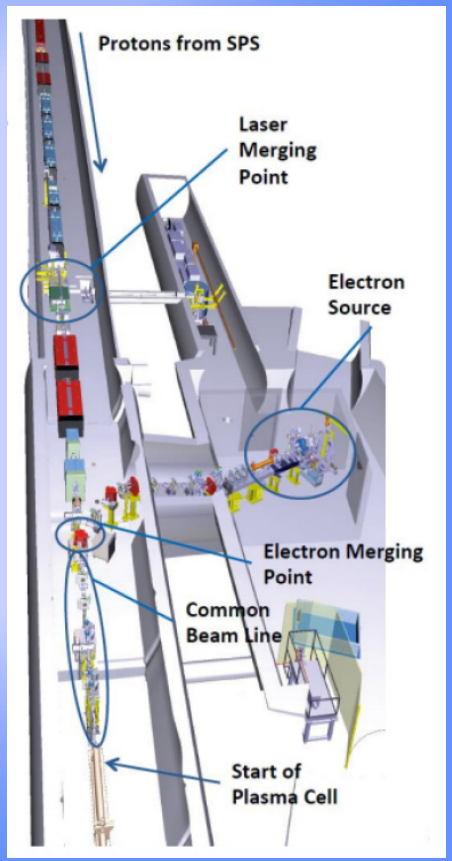
Seeded Self Modulation (SSM)



A seeded self modulation transverse instability transforms the long bunch in a series of micro bunches which drive resonantly the longitudinal wake field

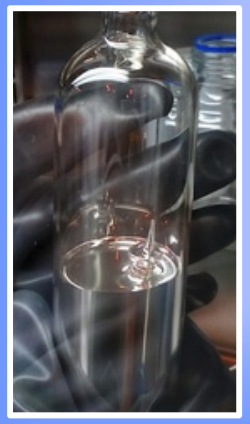
The AWAKE experiment at CERN



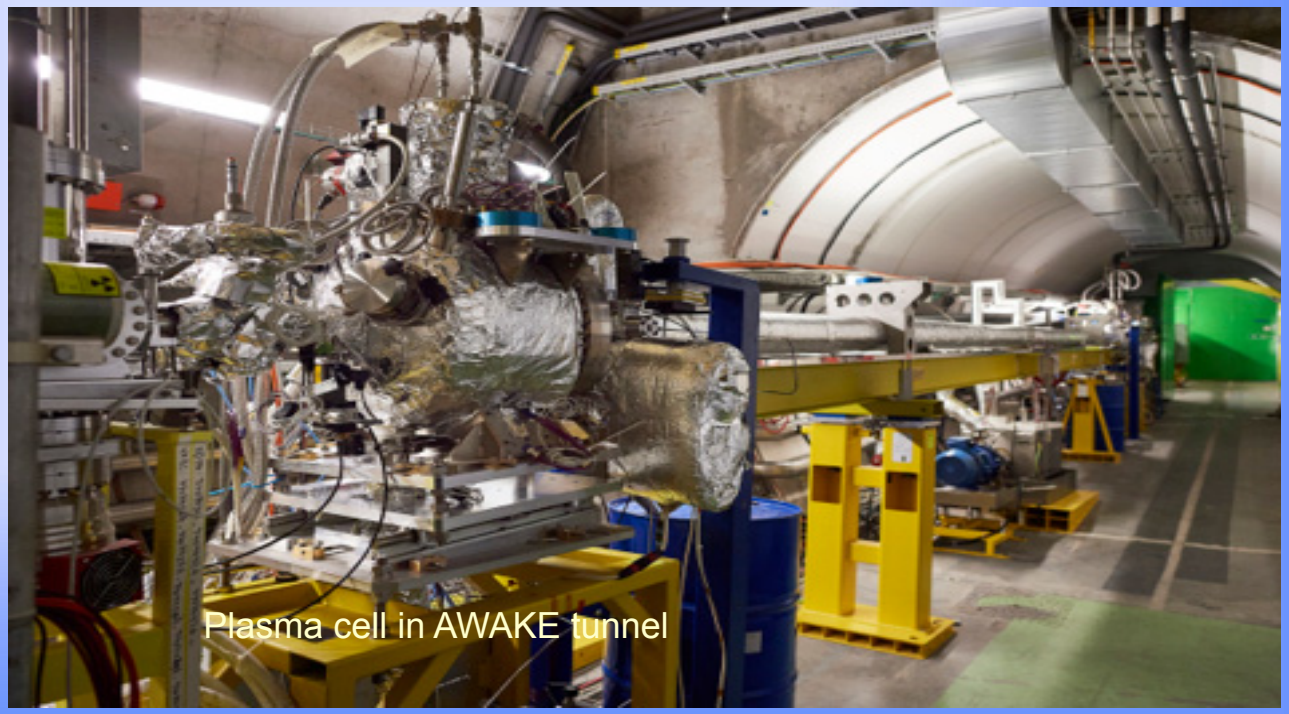


The plasma cell
This is our LINAC

10 m long, Ø 4 cm
Rubidium vapor (~200 °C)
Density: 10^{14}-10^{15} cm^{-3}
Uniformity: < 0.2 %

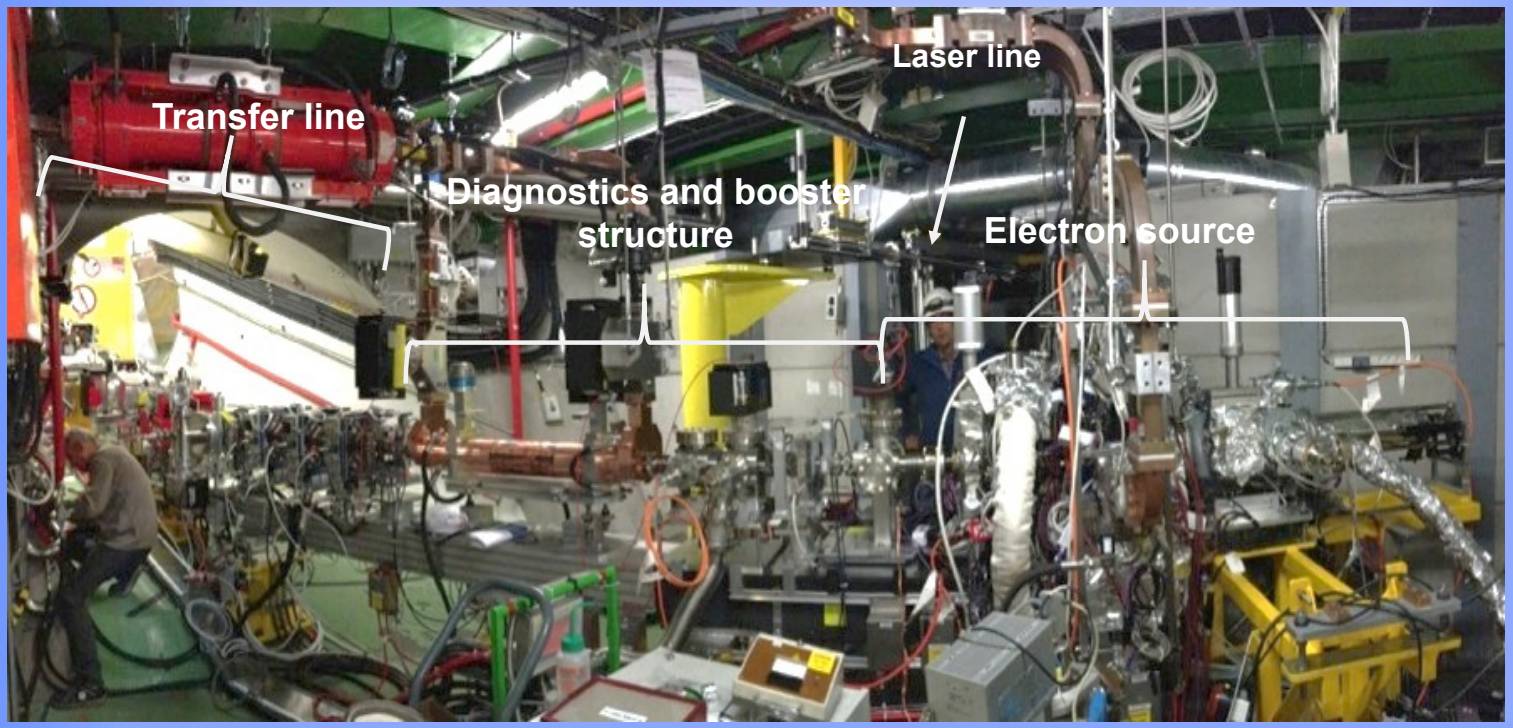


Rubidium flask



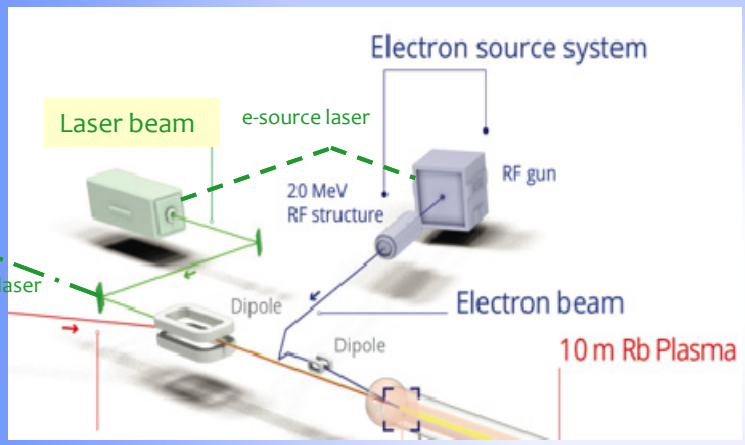
Plasma cell in AWAKE tunnel

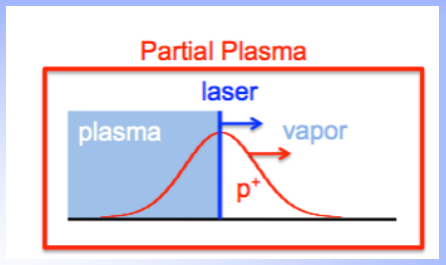
The electron injector

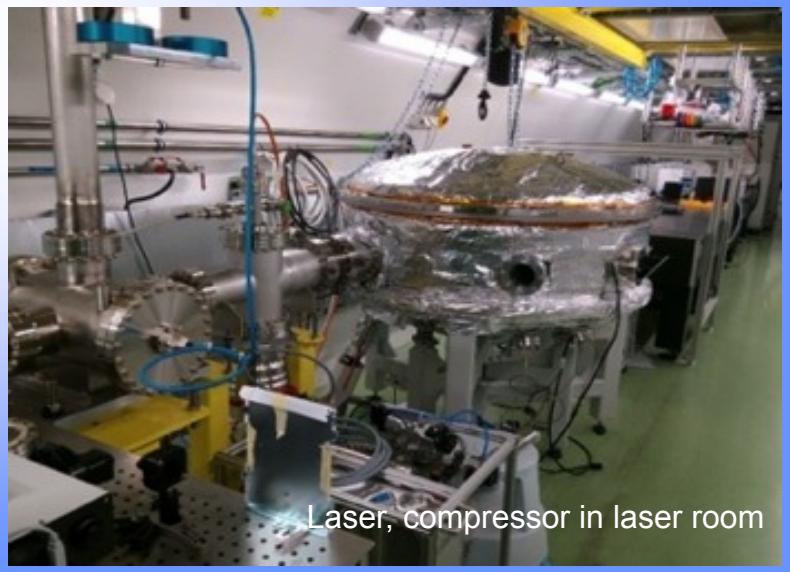


→ Laser on Cs_2Te cathode produces electron bunch with σ ~2ps, ~650pC. → 2.5 cell RF-gun accelerates to 6 MeV → 30 cell travelling wave structure accelerates up to 20 MeV → 18m long beam line to plasma cell.

Ionisation and seed laser



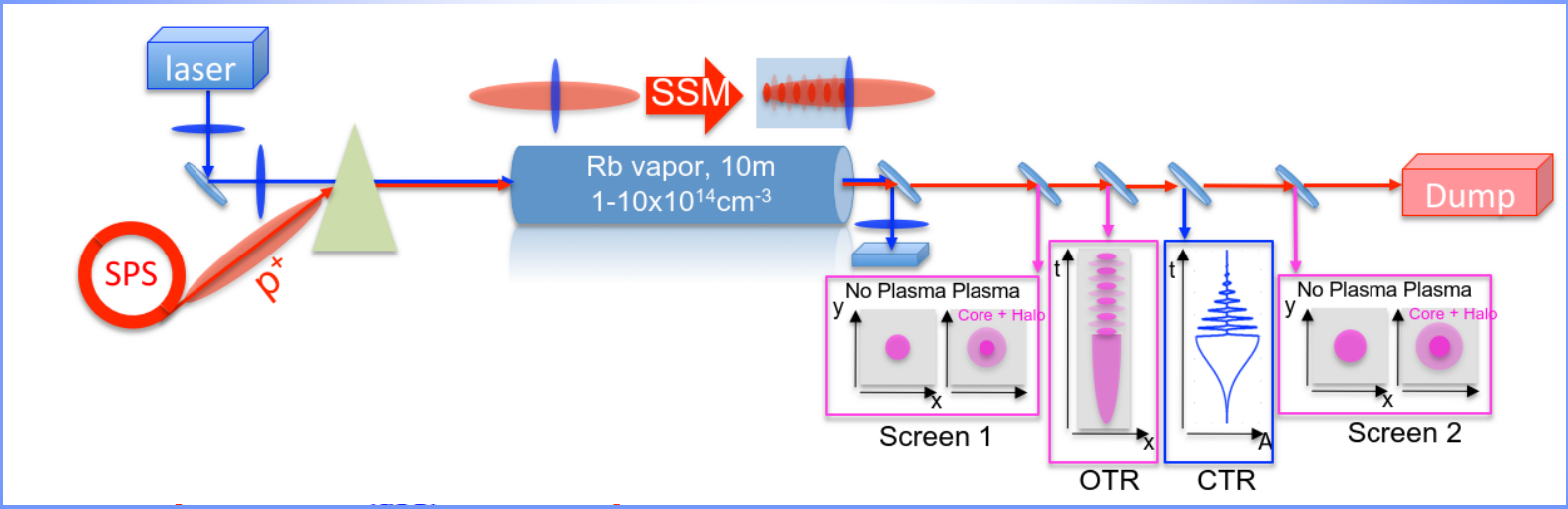




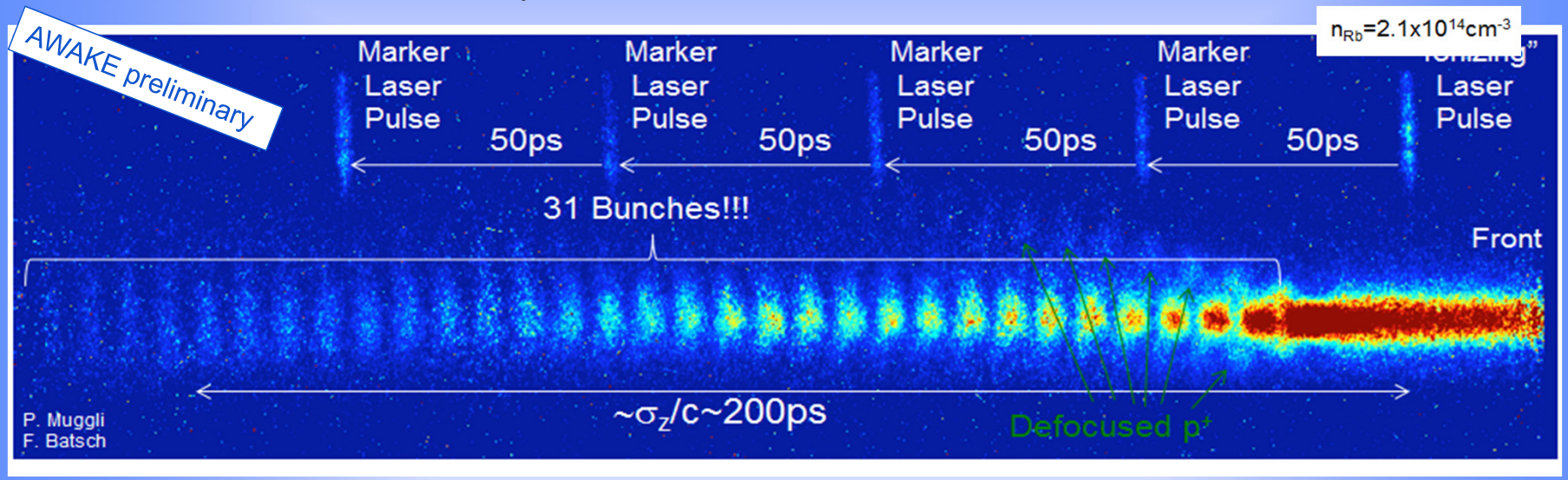
- Fiber/Ti-Sapphire laser: 120 fs, E_{max} = 450 mJ
- Rb: 4.177 eV
- R_o ~1 mm, Z_R ~ 5 m, $I_{max} > 10^{13}$ Wcm^{-2}

Diagnostics

- Screens and BPM's for proton, electron and laser alignment
- Screens behind plasma cell for proton defocusing (halo) detection
- OTR screen for time resolved measurements with the streak camera and temporal alignment
- CTR diagnostics to measure micro bunching frequency with heterodyne system



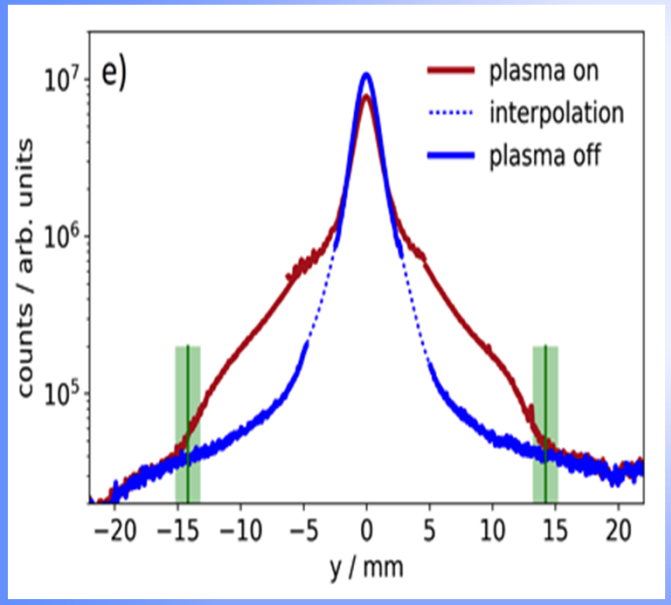
Seeded Self Modulation (SSM) Experimental observations



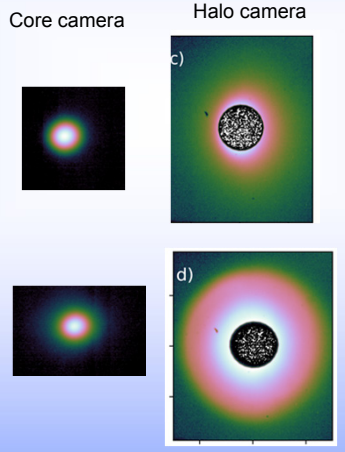
- Stable and reproducible modulation observed over a long time.
- Phase stability checked with marker laser; → suitable for electron injection
- Proton defocusing clearly visible
- Modulation frequency according to theory
- In this case 131 GHz standing wave accelerating structure

Seeded Self Modulation (SSM) Experimental observations

Combination of core and halo image projections

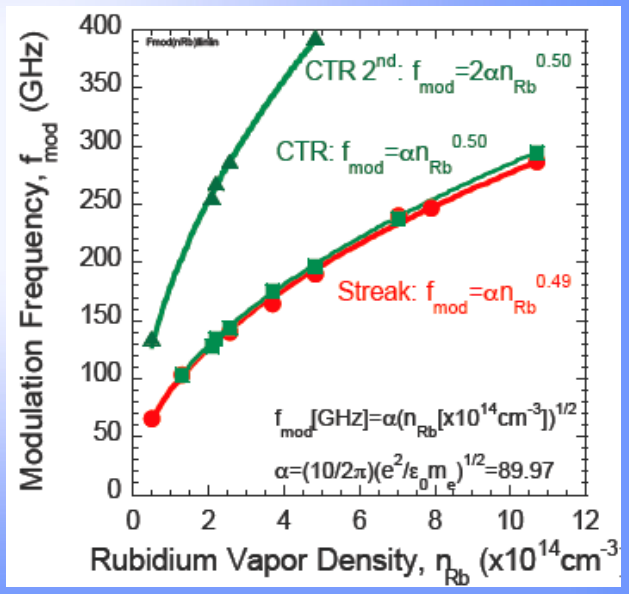


no plasma



plasma

Modulation frequency versus vapor density results

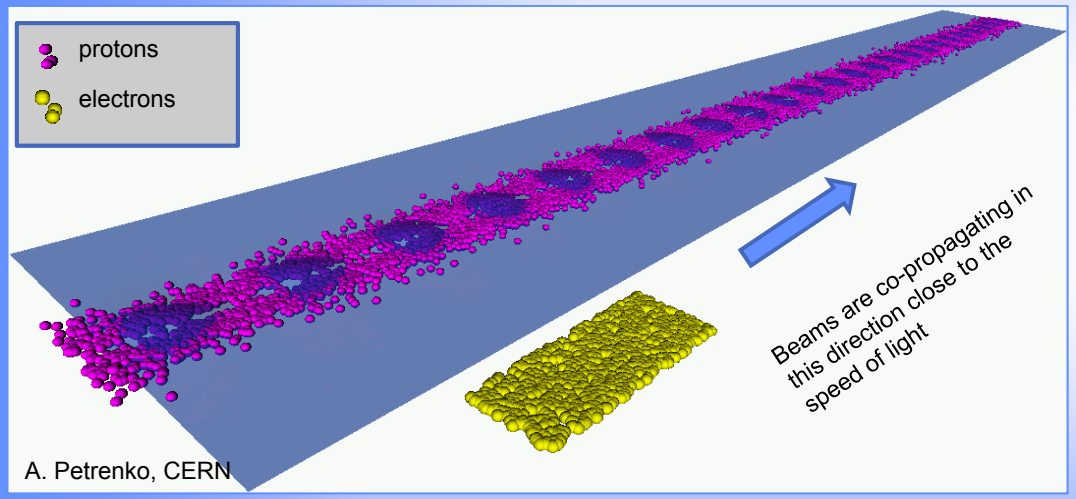


More details in: arXiv:1809.01191

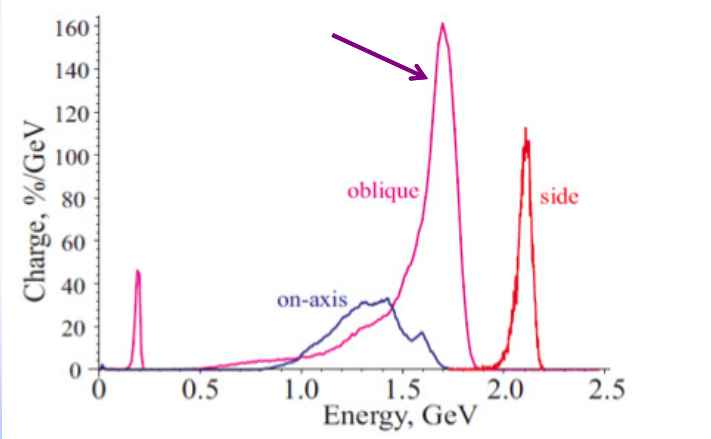
More details in: arXiv:1809.04478

Electron injection and acceleration

Electron acceleration after 10m: Simulation results

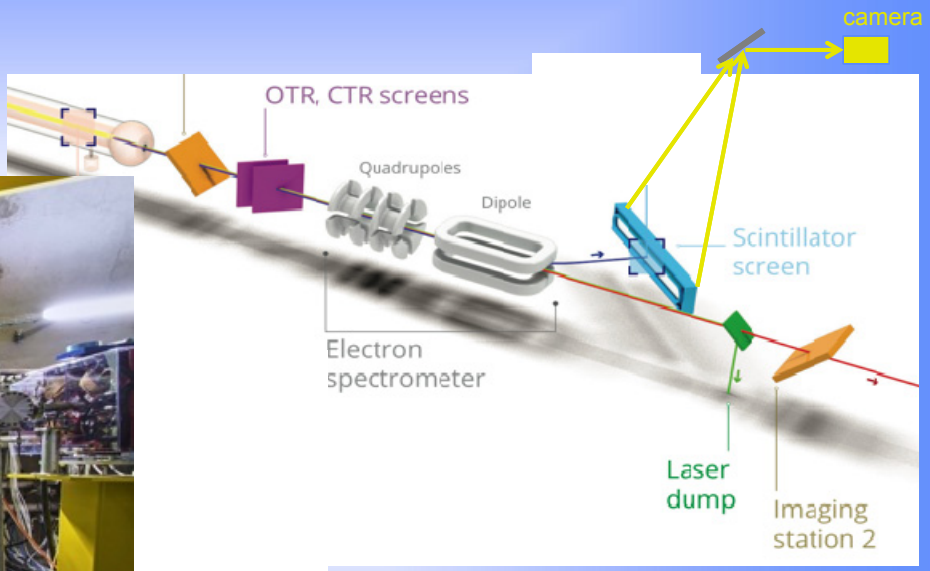


with baseline parameters: ~1.6 GeV



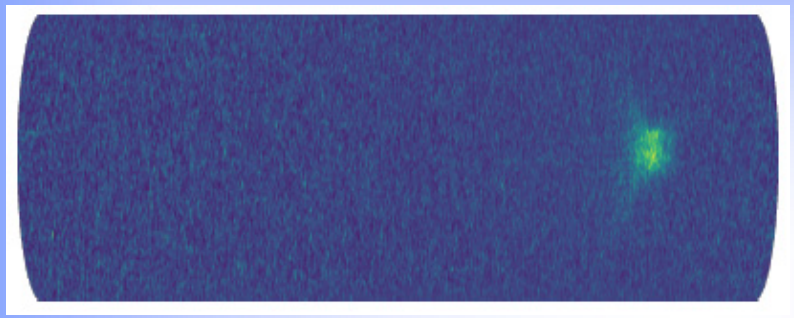
A. Caldwell et al., AWAKE Coll., Nucl. Instrum. A 829 (2016) 3

Electron spectrometer



Spectrometer:
Dipole: B = 0.1 - 1.5 T, Magnetic length = 1m
→ detect electrons with energies ranging from 30MeV - 8.5 GeV

First demonstration of electron acceleration in PD-PWA



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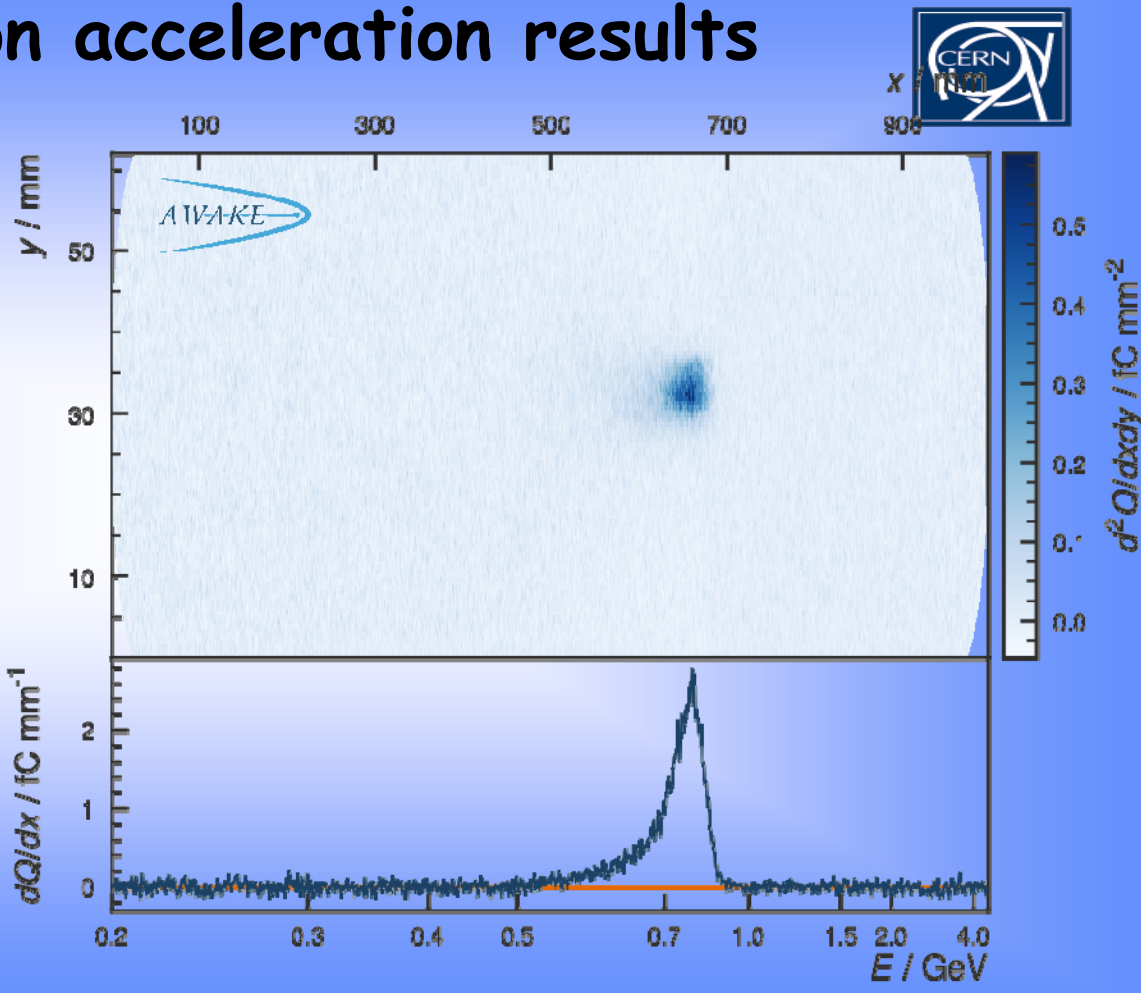
LETTER
doi:10.1038/s41586-018-0485-4

Acceleration of electrons in the plasma wakefield of a proton bunch

E. Adli, A. Ahuja, O. Apsimon, R. Apsimon, A.-M. Bachmann, D. Barrientos, F. Batsch, J. Bauche, V.K.Berglyd Olsen, M. Bernardini, T. Bohl, C. Bracco, F. Braunmüller, G. Burt, B. Buttenschön, A. Caldwell, M. Cascella, J. Chappell, E. Chevallay, M. Chung, D. Cooke, H. Damerau, L. Deacon, L.H. Deubner, A. Dexter, S. Doebert, J. Farmer, V.N. Fedosseev, R. Fiorito, R.A. Fonseca, F. Friebel, L. Garolfi, S. Gessner, I. Gorgisyan, A.A. Gorn, E. Granados, O. Grulke, E. Gschwendtner, J. Hansen, A. Helm, J.R. Henderson, M. Hüther, M. Ibison, L. Jensen, S. Jolly, F. Keeble, S.-Y. Kim, F. Kraus, Y. Li, S. Liu, N. Lopes, K.V. Lotov, L.Maricalva Brun, M. Martyanov, S. Mazzoni, D.Medina Godoy, V.A. Minakov, J. Mitchell, J.C. Molendijk, J.T. Moody, M. Moreira, P. Muggli, E. Öz, C. Pasquino, A. Pardons, F.Peña Asmus, K. Pepitone, A. Perera, A. Petrenko, S. Pitman, A. Pukhov, S. Rey, K. Rieger, H. Ruhl, J.S. Schmidt, I.A. Shalimova, P. Sherwood, L.O. Silva, L. Soby, A.P. Sosedkin, R. Speroni, R.I. Spitsyn, P.V. Tuev, M. Turner, F. Velotti, L. Verra, V.A. Verzilov, J. Vieira, C.P. Welsch, B. Williamson, M. Wing, B. Woolley and G. Xia

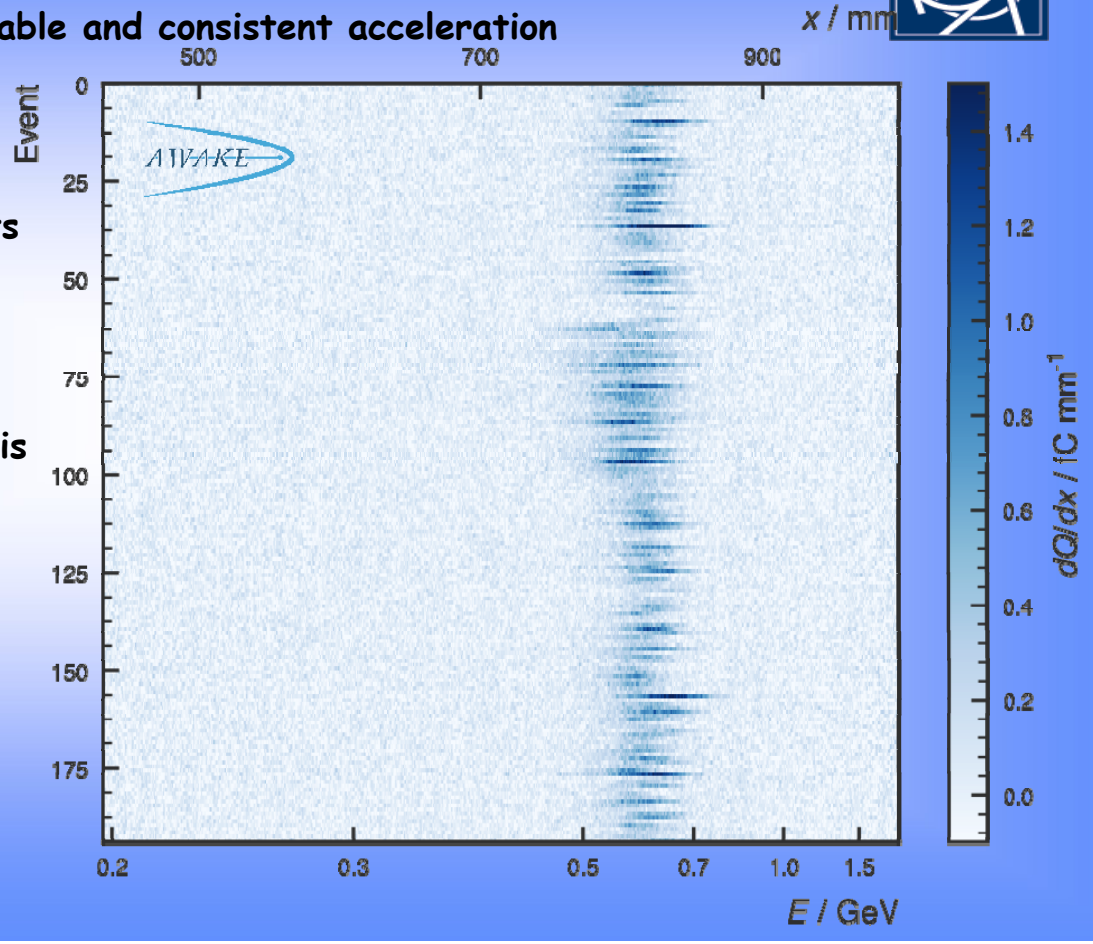
Electron acceleration results

- Event at n_{pe} =1.8 x 10^{14} cm^{-3} with 5%/10m density gradient.
- Acceleration to 800 MeV.
- Energy is dependent on n_{pe} and on the gradient.
- Accelerated bunch charge of 0.2pC → Capture efficiency not yet optimized.



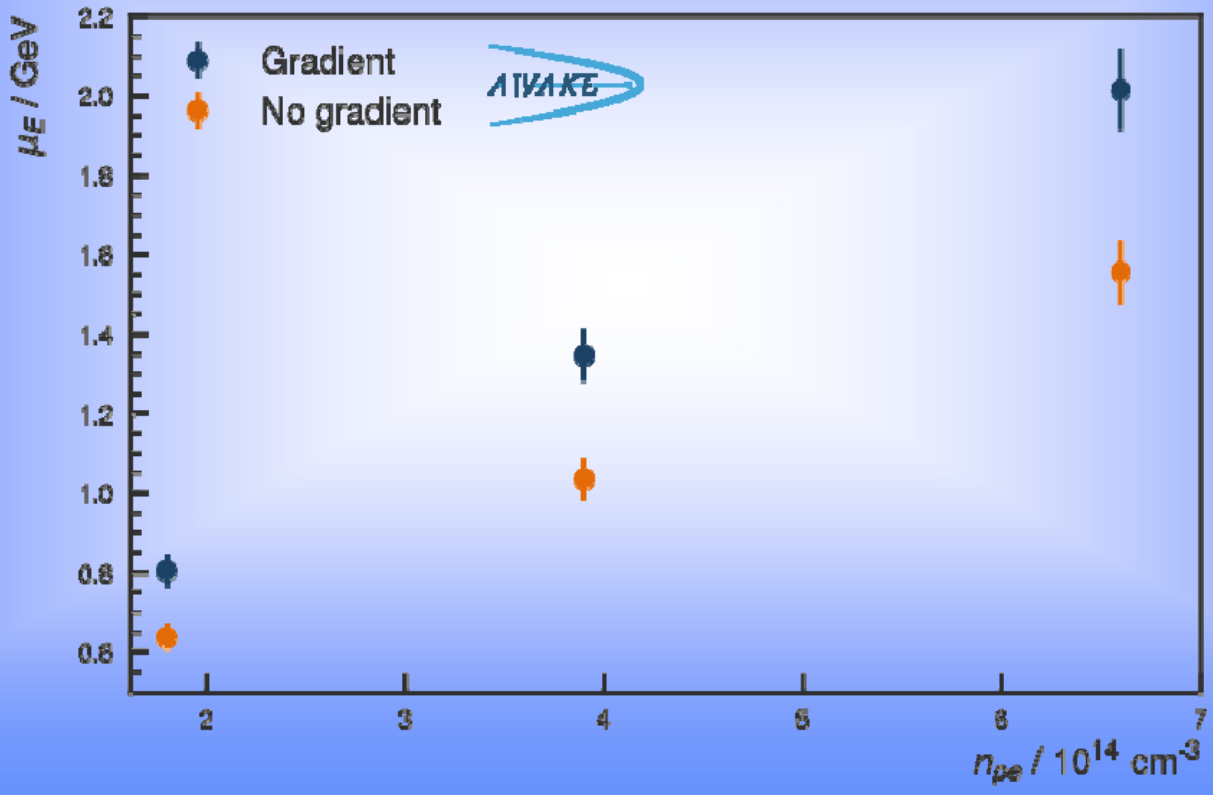
Electron acceleration results

- Consecutive electron injection events at $n_{pe} = 1.8 \times 10^{14} cm^{-3}$.
- Quadrupole scan performed over this period.
- Stability crucial for further development.



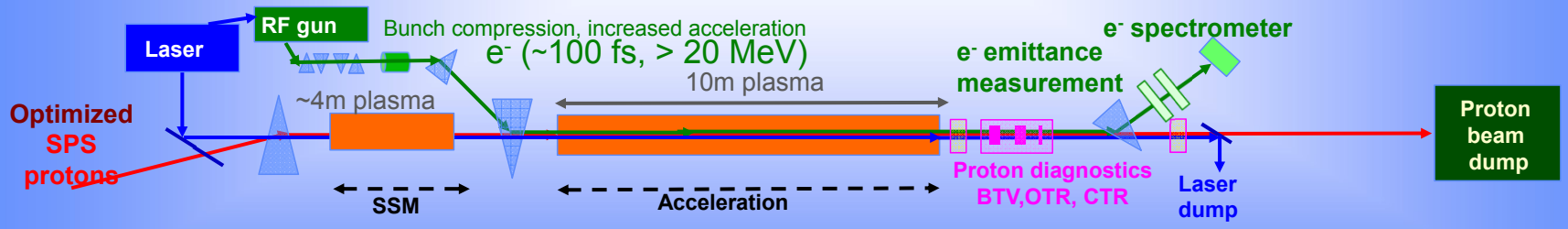
Electron acceleration results

Energy gain as function of plasma density



Outlook, AWAKE Run2, 2020+

- Separate SSM and pure acceleration, scalable plasma cells
- Emittance preservation and low energy spread
- Acceleration of electron beams of 10's of GeV suitable for high energy physics experiments



E. Adli (AWAKE Collaboration), IPAC 2016 proceedings, p.2557 (WEPMY008)

Conclusion

- Awake has shown stable and reproducible seeded self modulation of a long proton bunch enabling proton driven plasma wakefield acceleration
- AWAKE has demonstrated for the first time electron acceleration in PDPWA
- The next steps in RUN 2 (2020+) will be to show scalable plasma cells and acceleration of high quality electron beams suitable for high energy physics experiments

AWAKE

AWAKE Collaboration: 18+3 Institutes world-wide:

Collaboration members:

- University of Oslo, Oslo, Norway
- CERN, Geneva, Switzerland
- University of Manchester, Manchester, UK
- Cockcroft Institute, Daresbury, UK
- Lancaster University, Lancaster, UK
- Max Planck Institute for Physics, Munich, Germany
- Max Planck Institute for Plasma Physics, Greifswald, Germany
- UCL, London, UK
- UNIST, Ulsan, Republic of Korea
- Philipps-Universität Marburg, Marburg, Germany
- Heinrich-Heine-University of Düsseldorf, Düsseldorf, Germany
- University of Liverpool, Liverpool, UK
- ISCTE - Instituto Universitéario de Lisboa, Portugal
- Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia
- Novosibirsk State University, Novosibirsk, Russia
- GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
- TRIUMF, Vancouver, Canada
- Ludwig-Maximilians-Universität, Munich, Germany

Associated members:

- University of Wisconsin, Madison, US
- Wigner Institute, Budapest
- Swiss Plasma Center group of EPFL

Electron injection