Beam Diagnostics in the Advanced Plasma Wakefield Experiment AWAKE

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on behalf of the AWAKE collaboration

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GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

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

Technische Universität München

Outline of the Talk

1. **Plasma Wakefield Accelerators and the AWAKE Experiment**

2. **Self-Modulation of a Long Particle Bunch in a Plasma**

3. **Diagnostics for the Self-Modulated Proton Bunch**
    1. Fluorescence Screens for Time Integrated Transverse Distribution
    2. Optical Transition Radiation with Streak Camera for Time Evolution
    3. Coherent Transition Radiation using Heterodyne Detectors for Modulation Frequency Measurements

4. **Diagnostics for the Accelerated Electron Bunch**
    Spectrometer for Charge, Energy, Energy Spread and Emittance Measurements

Additional Diagnostics & Conclusion

Plasma Wakefield Acceleration

Conventional Accelerators

Conventional Linear Machines

- Acceleration in **RF-cavities**
- Acceleration gradients limited by breakdown (<100 MeV/m)

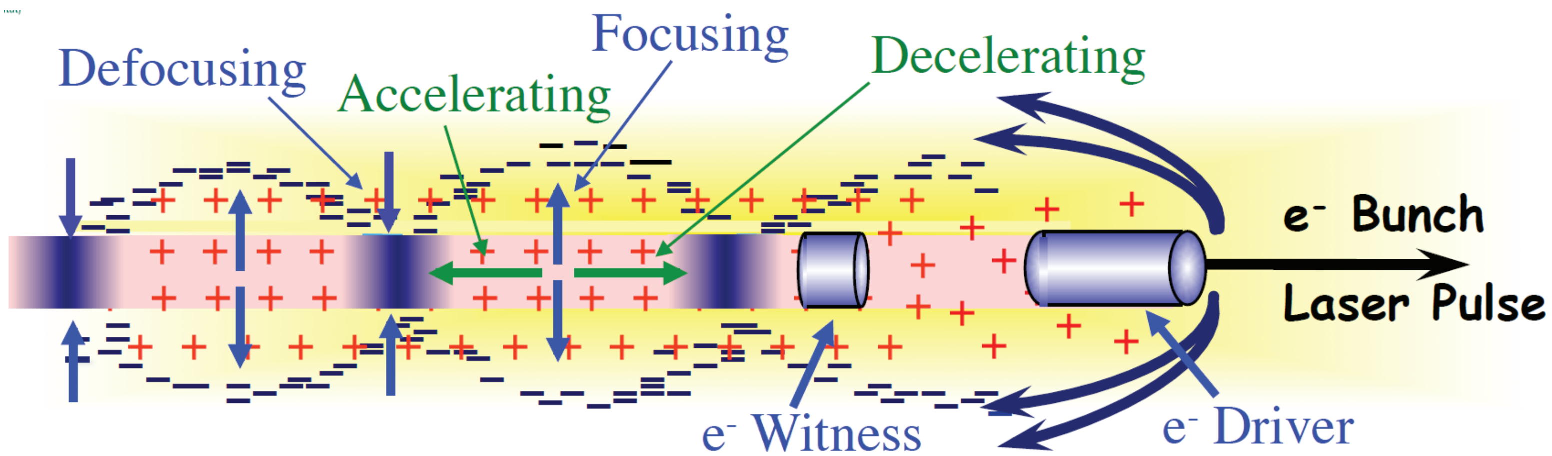
→ For higher particle energies: increase of accelerator size

3 km linear accelerator at SLAC,
$\Delta E = 17$ MeV/m 3 / 1

→ Research in advanced accelerators with stronger acceleration gradients
→ Promising candidate: **Plasma-wakefield accelerators (PWFA)**
→ **Requires different and new diagnostics**

Plasma Wakefield Acceleration (PWFA)

→ Acceleration of particles in a plasma wakefield



Creation of **plasma wakefield inside** a plasma

- Driver (laser pulse or particle bunch) **pushing plasma electrons**
  → Plasma electron **oscillation**
  → Plasma wave with **accelerating + decelerating** and **focusing + defocusing** fields

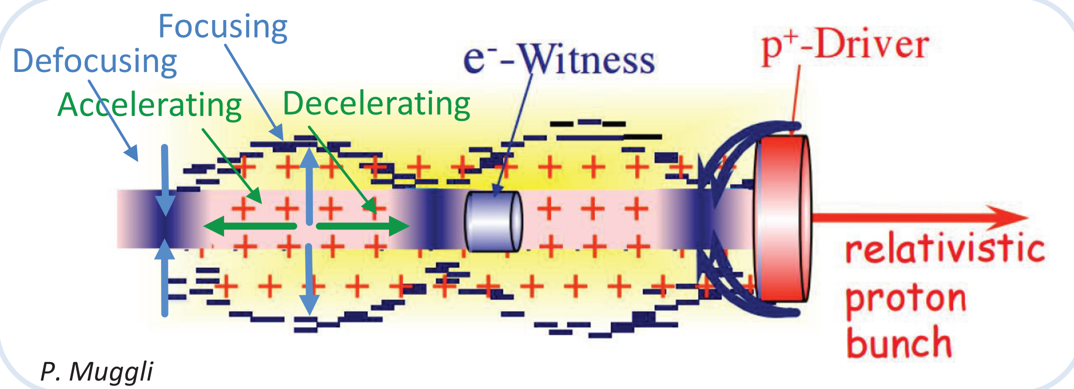
→ Relativistic witness beam sees **permanent acceleration** if injected at the right phase

- Overcomes break-down limitation of RF-accelerators
  (RF break down $< 100\ MV/m$, Wave breaking field $> 1\ GV/m$)
- Max energy gain: large fraction of drive bunch

Wave breaking field
$E_{WB} \propto n_e^{1/2}$

Plasma Wakefield Acceleration (PWFA)

→ Acceleration of particles in a plasma wakefield



electron plasma density n_{pe}

Plasma frequency: $\omega_{pe} = \sqrt{\frac{n_{pe} e^2}{\varepsilon_0 \, m_e}}$

$\lambda_{pe} \sim 1\ mm$ for $n_{pe} \sim 10^{15} cm^{-3}$

¼ of the period is accelerating and focusing

Driver for the Wakefields

- Previous plasma wakefield experiments: **Laser pulse** or negatively charged relativistic **electron bunch**
- **AWAKE**: **Proton bunch** (SPS at CERN) attracting plasma electrons
  → Driver with a larger amount of energy (3×10^{11} particles at 400GeV/p^+ carries over 19kJ)

Bunch size and length $\sigma_r, \sigma_z \leq c/\omega_{pe} \propto n_e^{-1/2}$

When $\sigma_z \gg c/\omega_{pe}$ ⟹ **Self-Modulation**

Self-Modulation of a Long Particle Bunch in a Plasma

Introduction Self-Modulation of a Long Particle Bunch in a Plasma

How does Self-Modulation occur?

Growth Mechanism

Seed (transverse) wakefields

↓

Periodic focusing/defocusing

↓

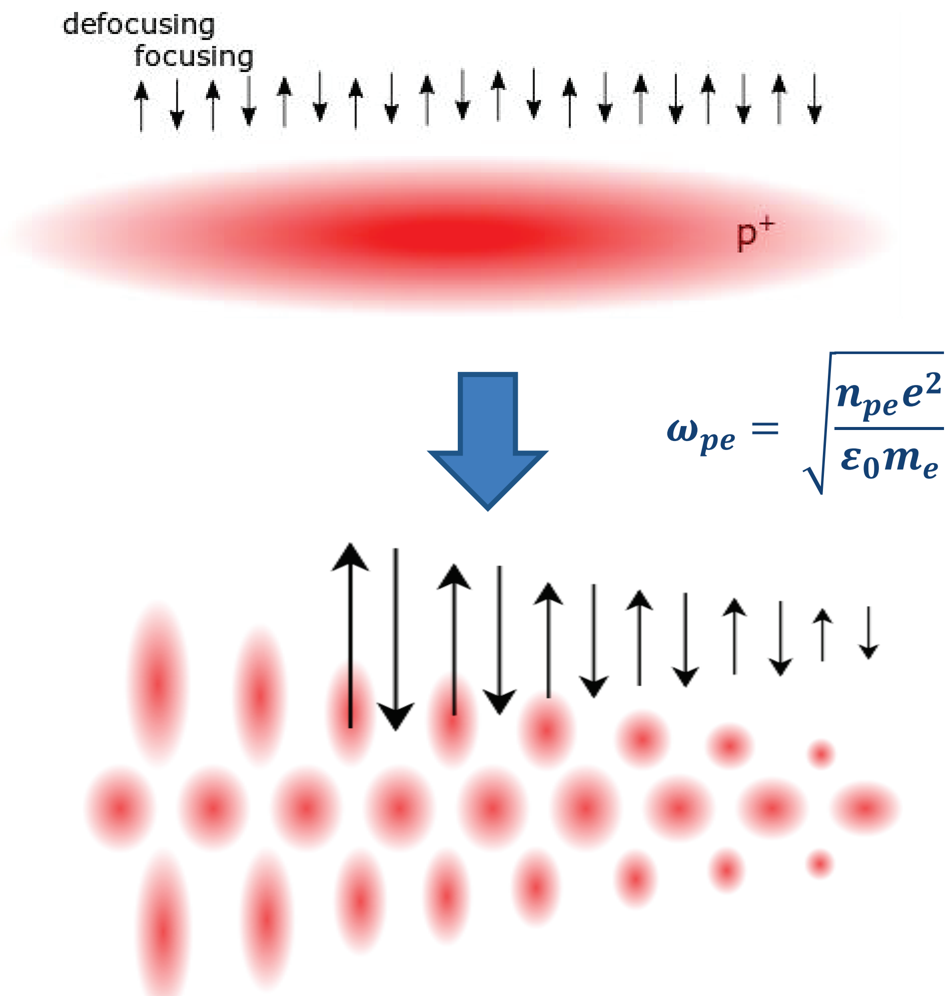
Radial/density modulation

↓

Stronger wakefields

↓

Full modulation – bunch train



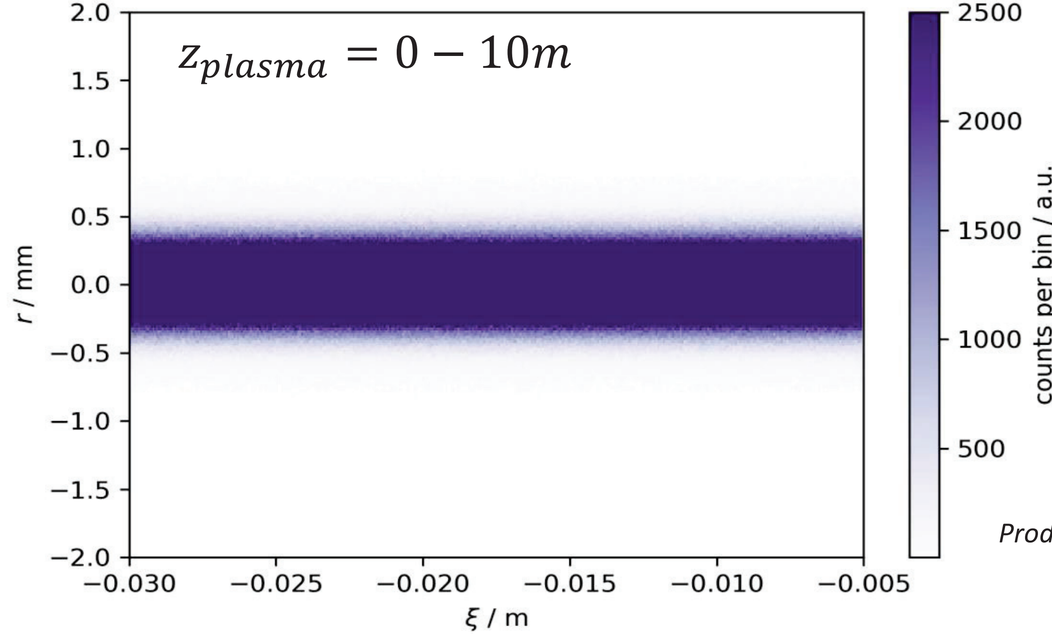
$$\omega_{pe} = \sqrt{\frac{n_{pe} e^2}{\varepsilon_0 m_e}}$$

→ **Self-modulation of long drive bunch into micro bunches shorter than and separated by the plasma wavelength $\lambda_{pe} = 2\pi c / w_{pe}$**

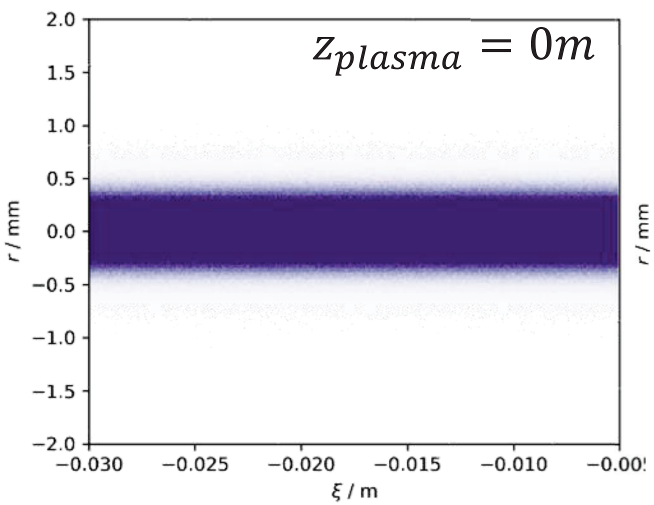
Introduction Self-Modulation of a Long Particle Bunch in a Plasma

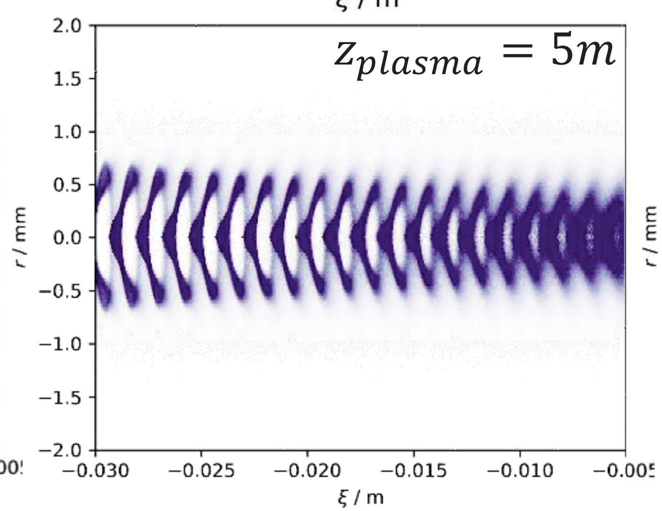
Simulation of self-modulation of the proton bunch

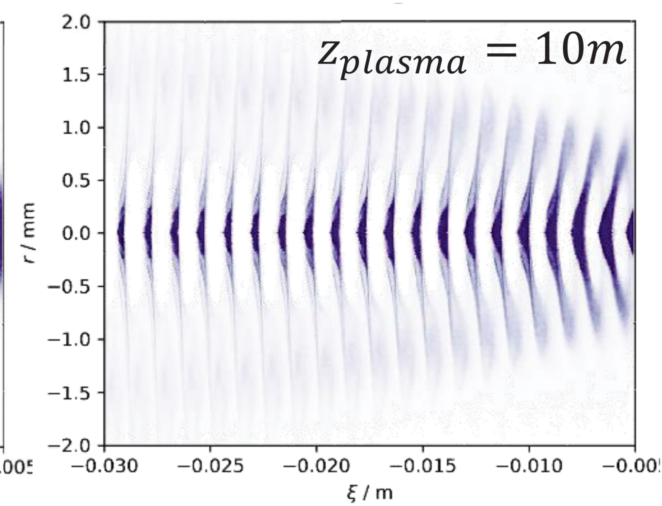
Radial Modulation



Produced with LCODE

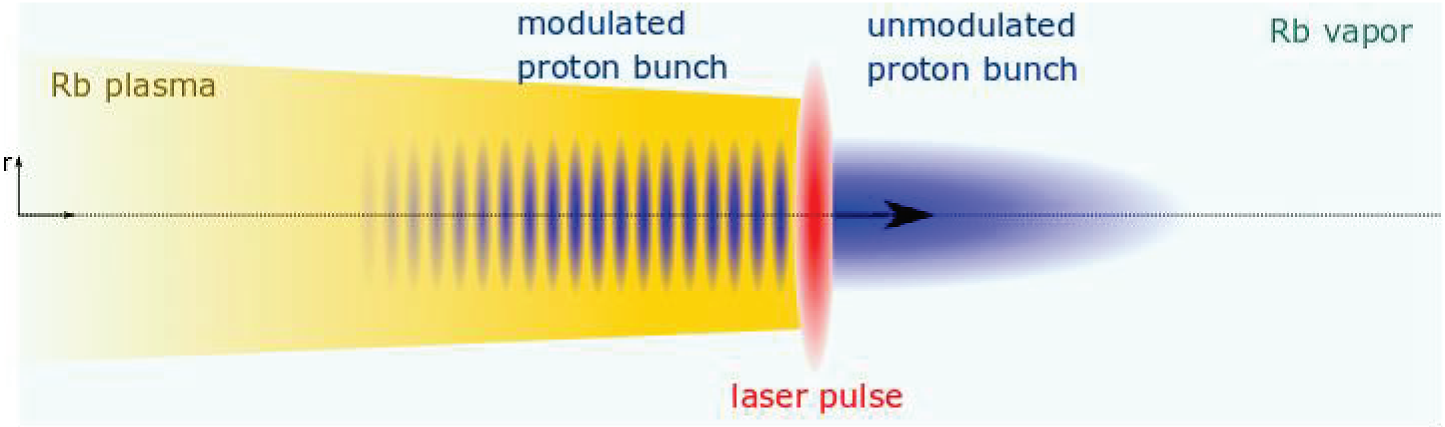






How can we seed self-modulation?

Seeding with relativistic ionization front



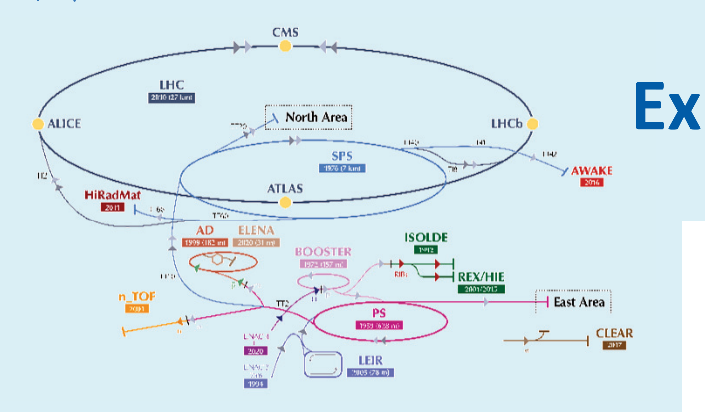
Laser pulse copropagating with the p^+ bunch

→ Sharp ionization front (plasma density step) provides initial wakefields

→ Seed wakefield amplitude if initial wakefields exceed the noise

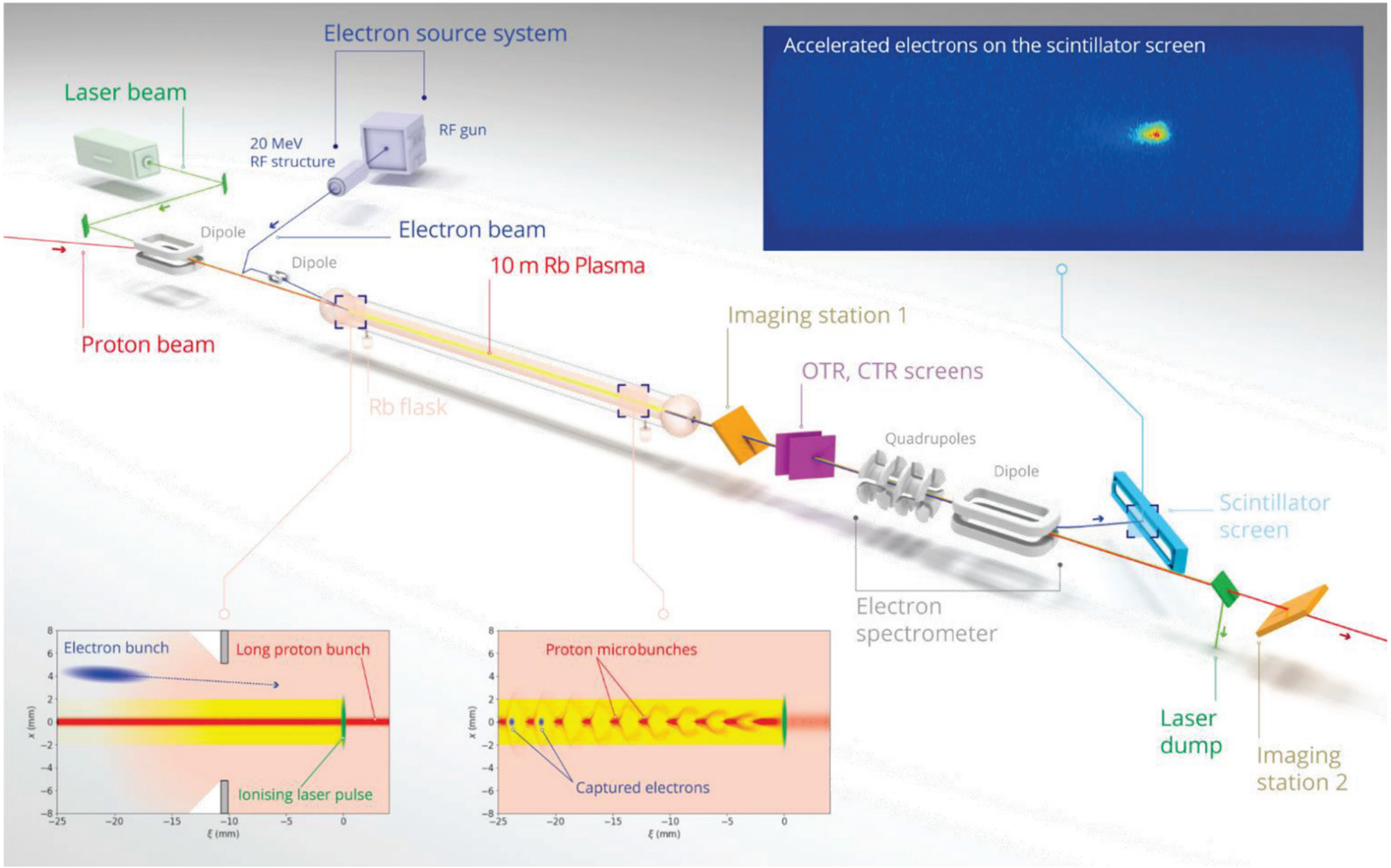
→ Phase reproducible modulation of the long proton bunch into micro bunches when seeded

Experimental Setup And Diagnostics for the Self-Modulated Proton Bunch

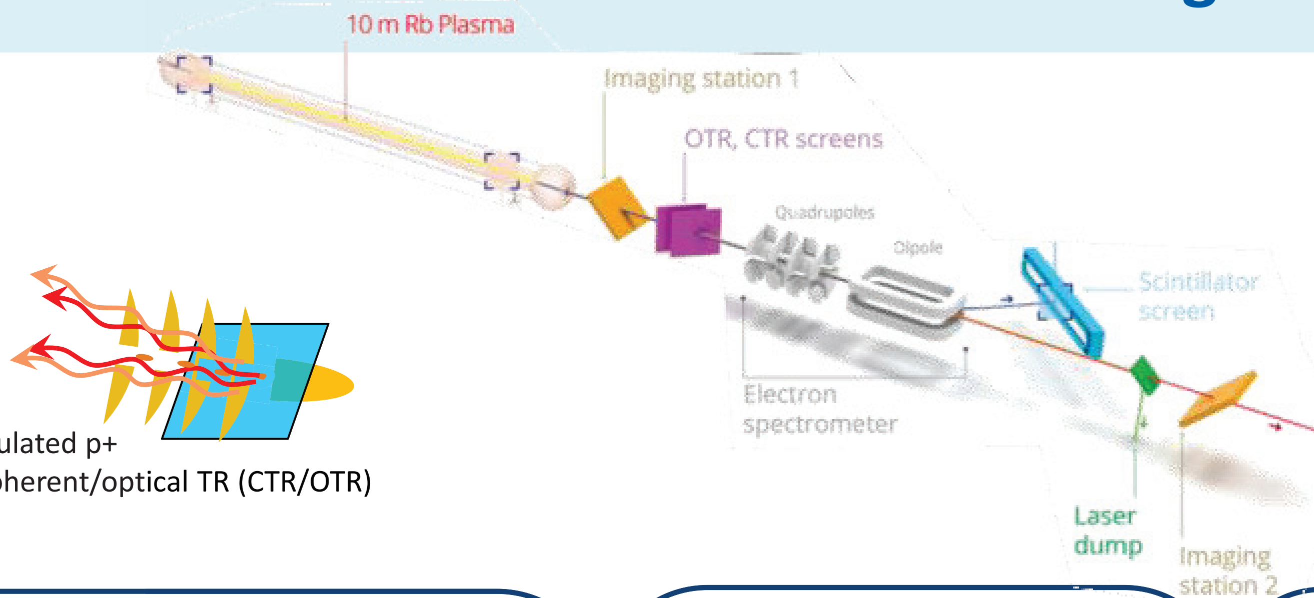


Experimental Setup of AWAKE

- 10m long **rubidium (Rb) vapor source**
- A 4TW **laser ionizing** the Rubidium vapor
- Driver: 400 GeV **proton bunch** from CERN's SPS accelerator
- Injection of a **witness electron bunch for acceleration**

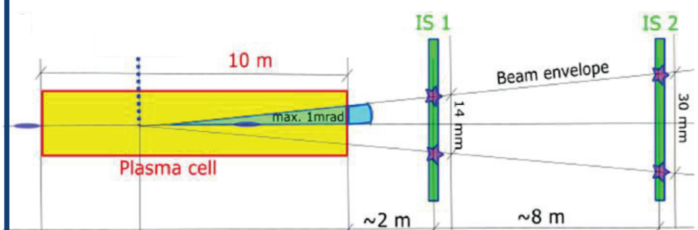


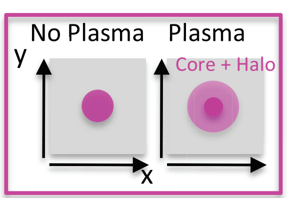
Modulated Proton Bunch Diagnostics



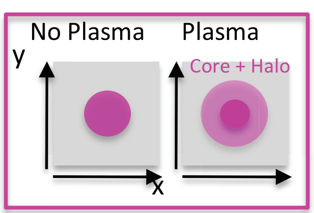
Modulated p+
→ coherent/optical TR (CTR/OTR)

Imaging station 1 & 2



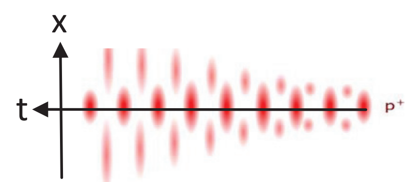


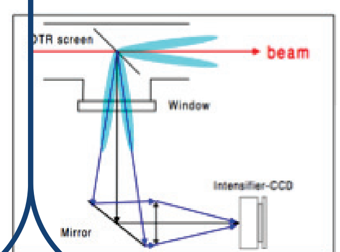
Screen 1



Screen 2

Streak Camera (OTR):





Streak Camera
≤1ps resolution

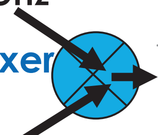
CTR-diagnostics:

$f_{modulation}$ (90-280GHz)

Signal:
f_{CTR} ~260GHz

Intermediate frequency:

Mixer

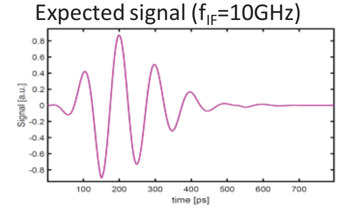


f_{IF} ~5-20GHz

Reference:
f_{ref}~270GHz

Oscilloscope

Expected signal (f_{IF}=10GHz)

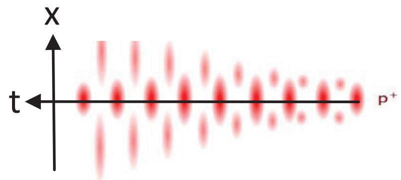


Diagnostic for Time Integrated Self-Modulated Proton Bunch
Two Screen Measurement for Modulated Proton Bunch

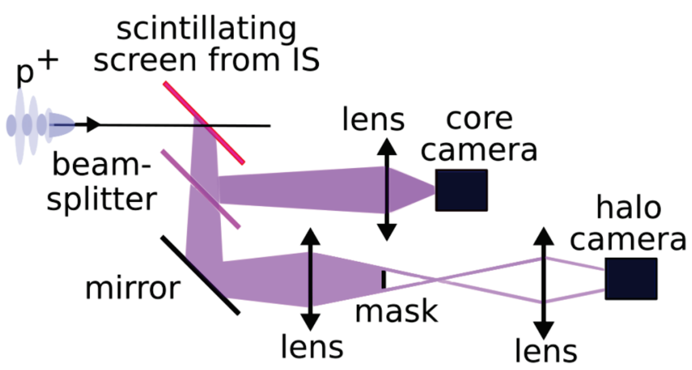
M. Turner et al., (AWAKE Collaboration), Phys. Rev. Lett. 122, 054801 (2019)

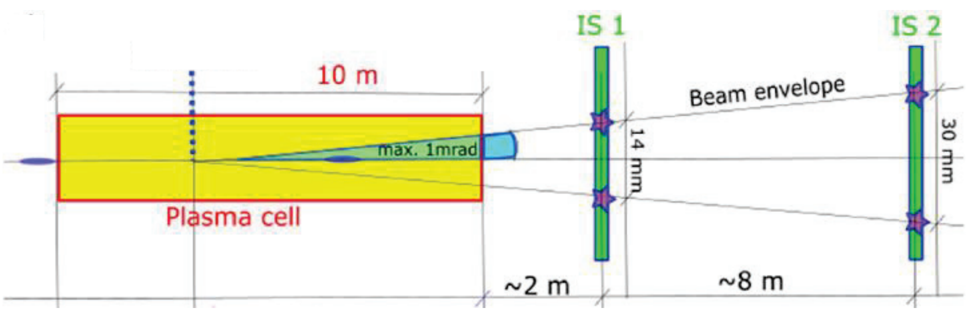
Transverse wakefields in plasma

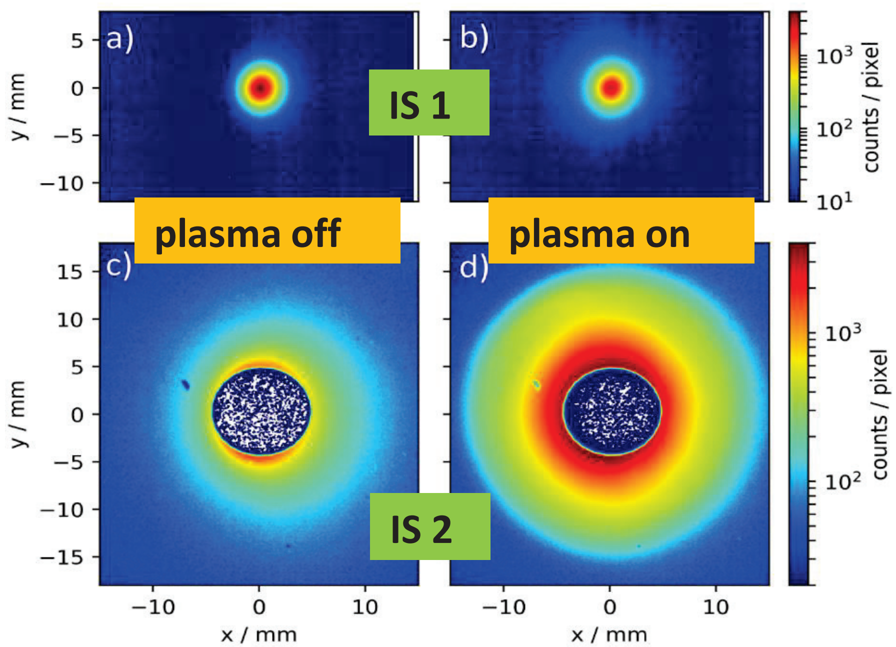
→ Defocusing of protons between micro-bunches



→ Larger radius for time integration







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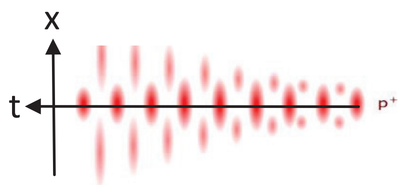
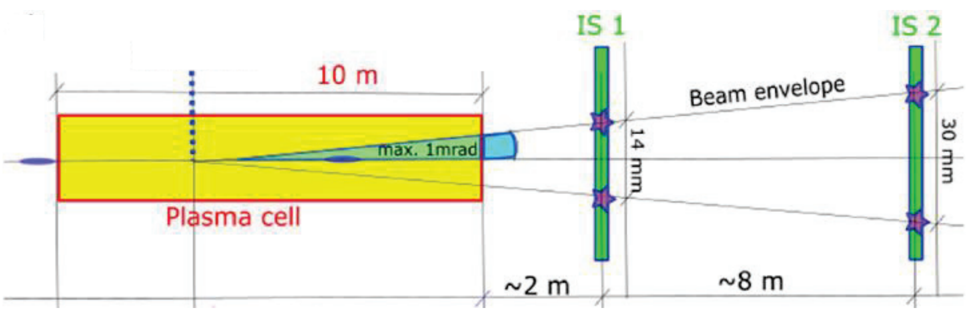
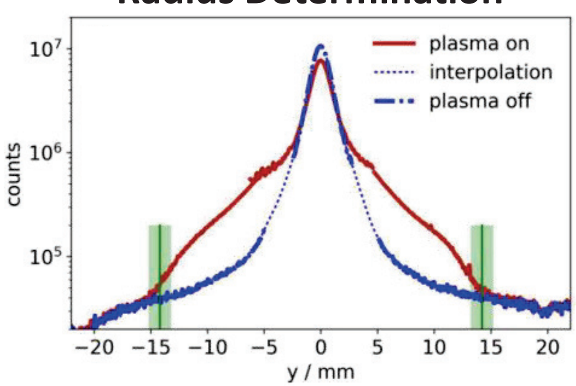


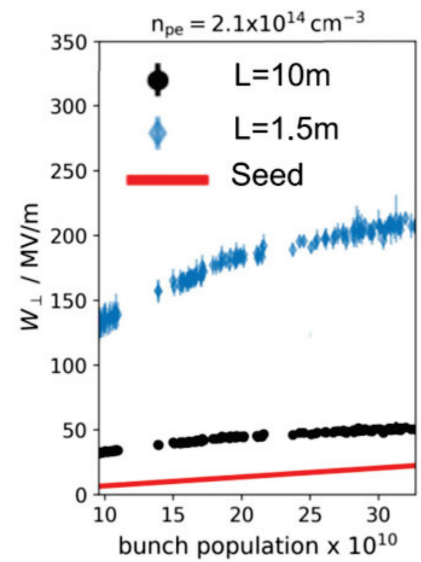


→ Larger radius for time integration

Radius Determination



Wakefield Amplitude Determination



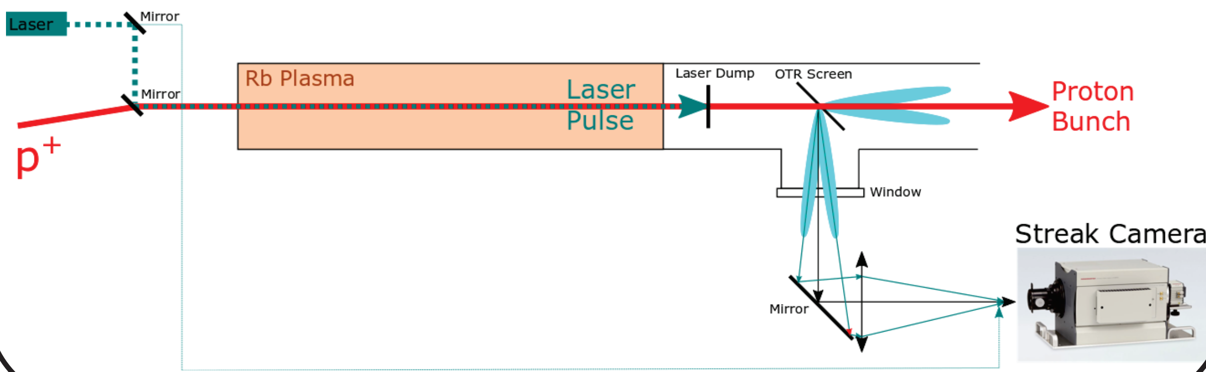
Growth along the plasma

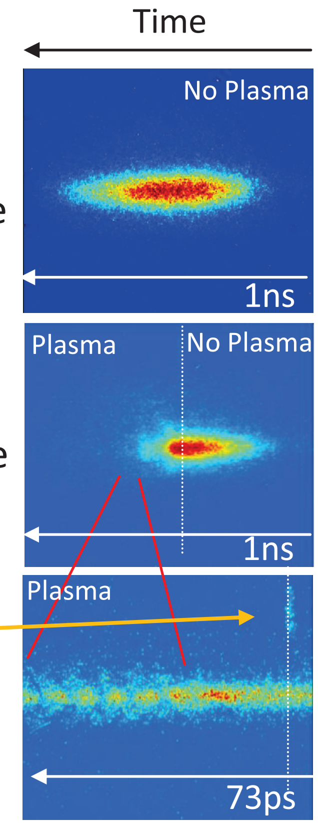
→ Wakefields grow along the plasma

Diagnostic for Time Resolved Self-Modulated Proton Bunch
Streak camera for Optical Transition Radiation (OTR)

K. Rieger *et al.*, Rev. of Scientific Instruments 88, 025110 (2017)

Modulated proton bunch through metal foil
→ Generation of OTR





Slow timescale

Slow timescale

Fast timescale

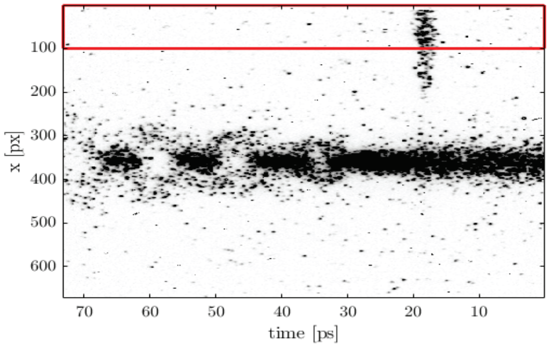
OTR prompt → time history of transverse density distribution

Imaging OTR screen onto the camera entrance slit
- → **Transverse bunch density distribution**
- → Higher light intensity than conventional used
- → Decrease of time resolution (space charge effect)

Timing **jitter of trigger** for streak camera
→ **Timing reference signal** from very small fraction of the ionizing laser pulse

Diagnostic for Self-Modulated Proton Bunch
Streak camera for Optical Transition Radiation (OTR)

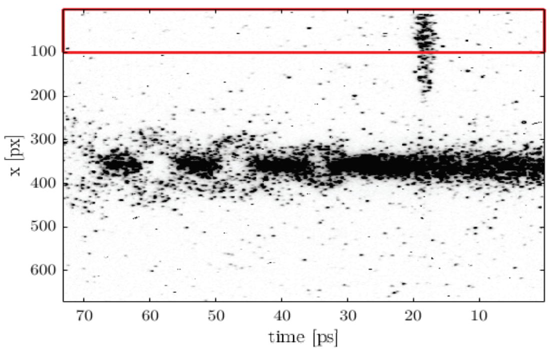
Acquisition of multiple events



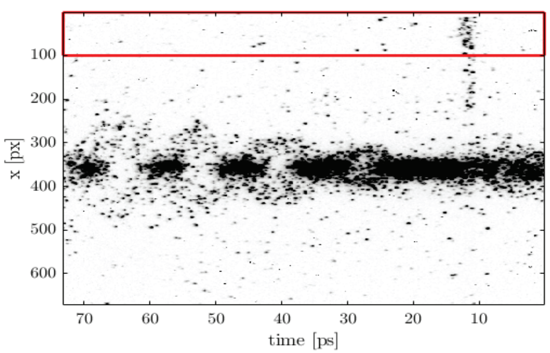
Event 1

Diagnostic for Self-Modulated Proton Bunch
Streak camera for Optical Transition Radiation (OTR)

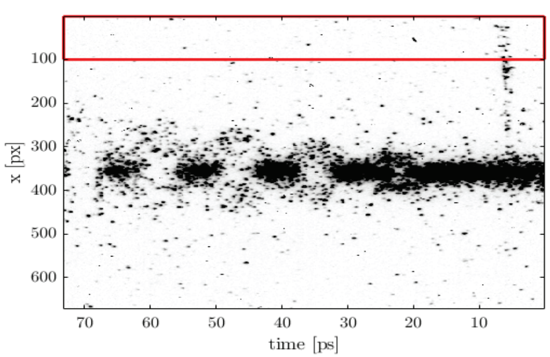
Acquisition of multiple events



Event 1



Event 2

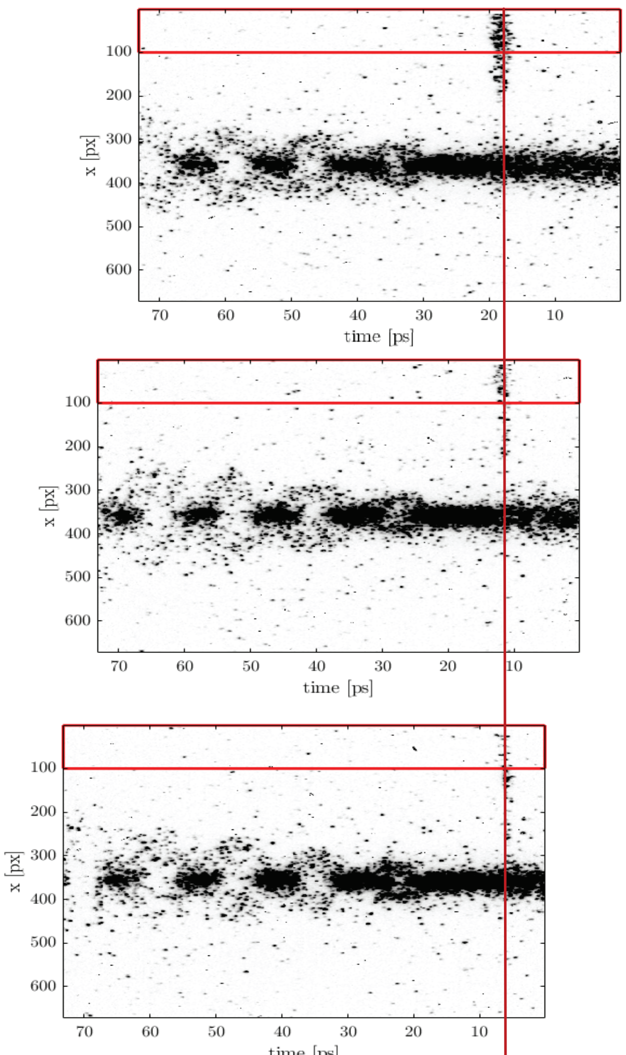


Event 3

Temporal jitter

Diagnostic for Self-Modulated Proton Bunch
Streak camera for Optical Transition Radiation (OTR)

Acquisition of multiple events



Event 1

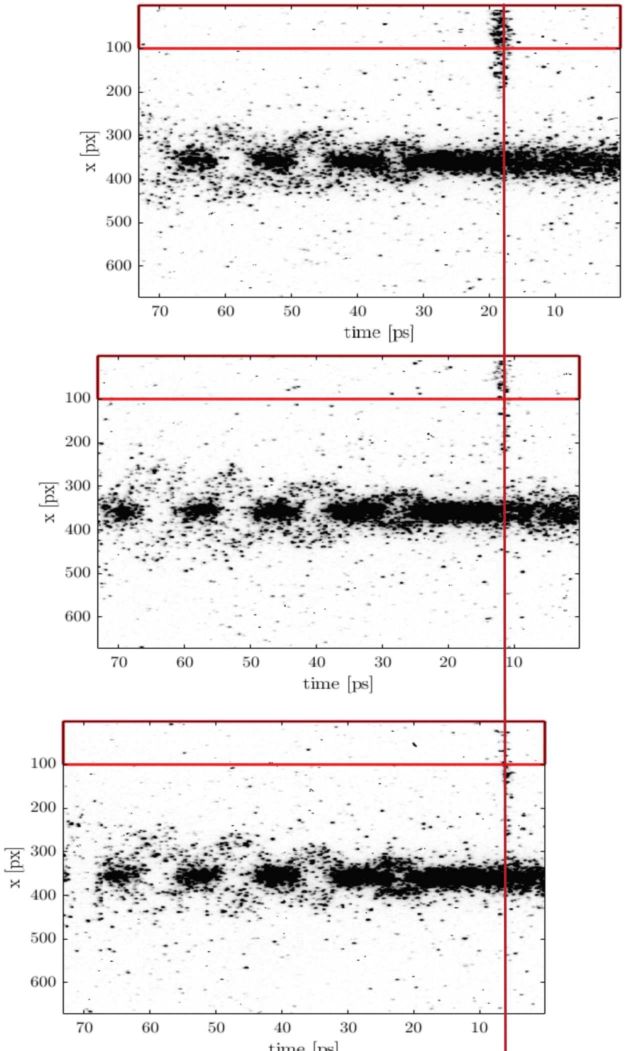
Event 2

Event 3

Temporal alignment with reference laser pulse

Diagnostic for Self-Modulated Proton Bunch
Streak camera for Optical Transition Radiation (OTR)

Acquisition of multiple events

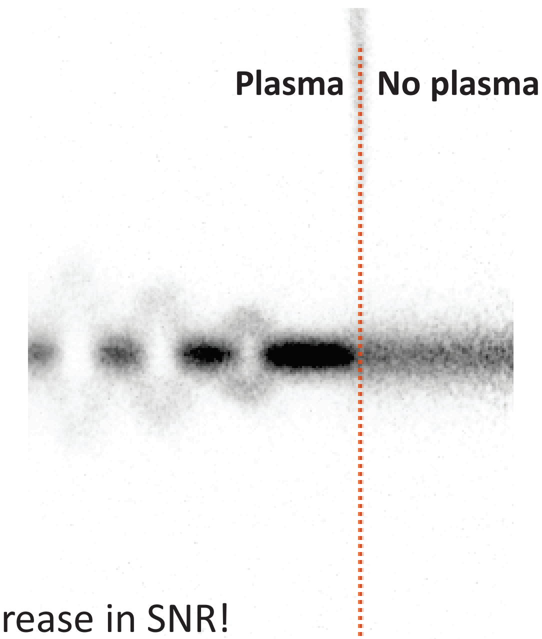


Event 1

Event 2

Event 3

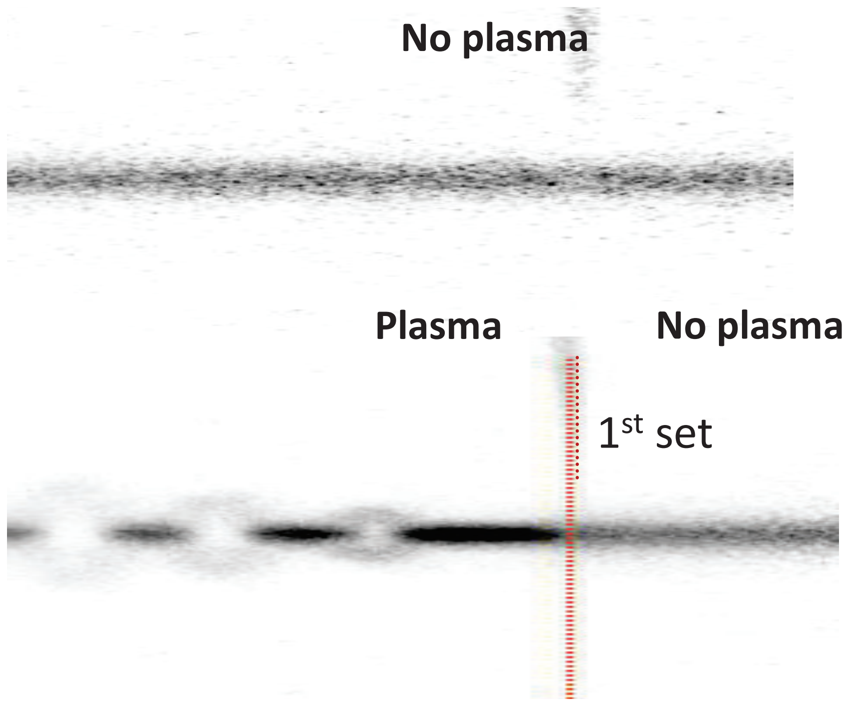
Averaging of 20 events



→ Increase in SNR!

Diagnostic for Self-Modulated Proton Bunch
Streak camera for Optical Transition Radiation (OTR)

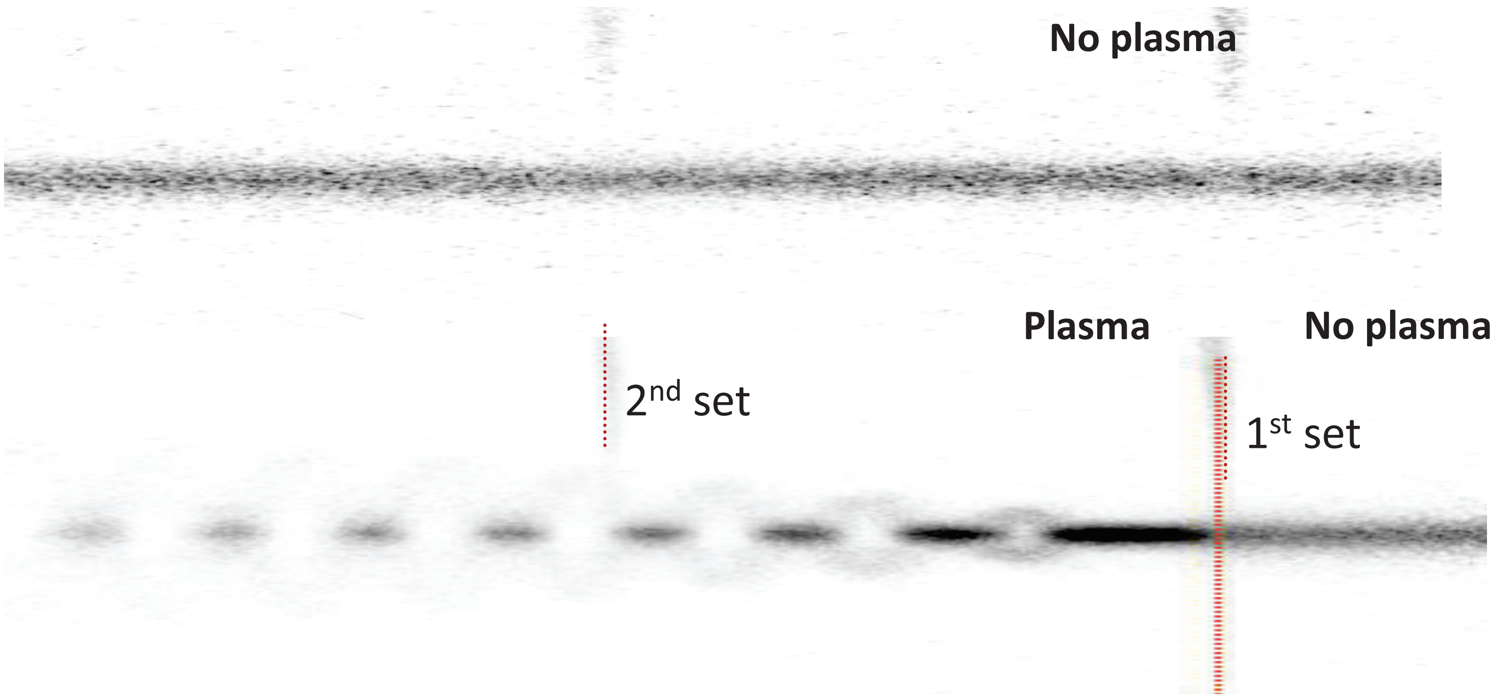
When modulation is phase reproducible....



→ Move streak camera window and time reference signal simultaneously

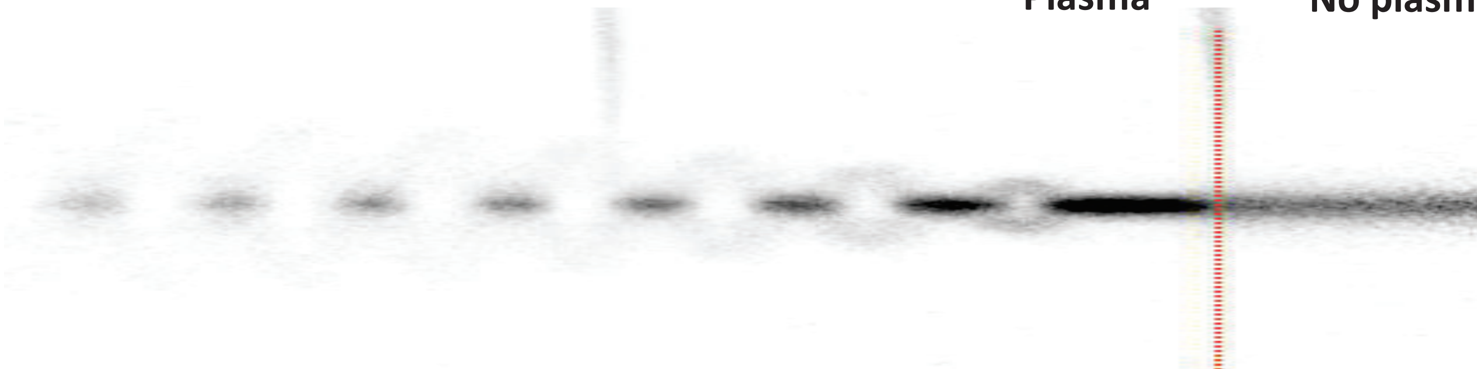
Diagnostic for Self-Modulated Proton Bunch
Streak camera for Optical Transition Radiation (OTR)

When modulation is phase reproducible....



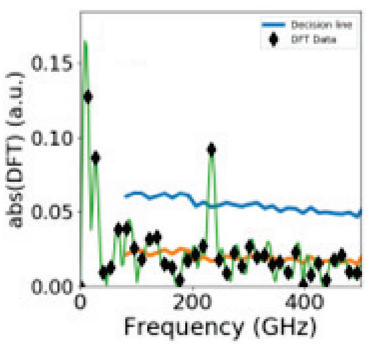
- → Move streak camera window and time reference signal simultaneously
- → We can scan along the bunch
- → Stitching of images with the shortest time window thus highest time resolution

Diagnostic for Self-Modulated Proton Bunch
Streak camera for Optical Transition Radiation (OTR)



Determination from streak camera images of

- **Modulation frequency from DFT of central bunch density map**



E. Adli et al. (AWAKE Collaboration), Phys. Rev. Lett. 122, 054802 (2019).

Diagnostic for Self-Modulated Proton Bunch
Streak camera for Optical Transition Radiation (OTR)

Determination from streak camera images of

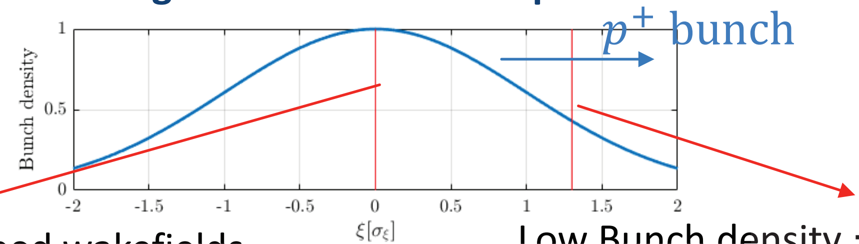
- **Micro-bunch length, size and relative charge** (taken the slit of the streak camera into account)

A.-M. Bachmann et al., accepted for publication in Journal of Physics: Conference Series 224 (JPCS) and arXiv:1912.02162

Diagnostic for Self-Modulated Proton Bunch
Streak camera for Optical Transition Radiation (OTR)

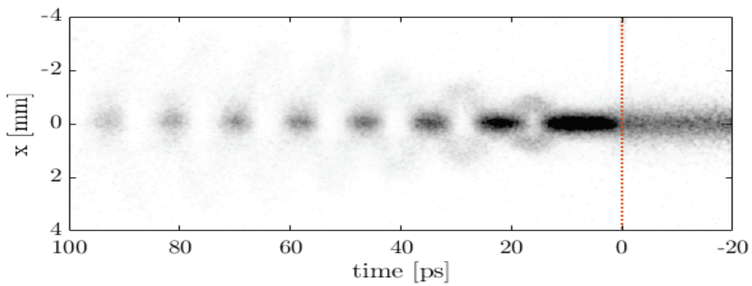
Determination from streak camera images of

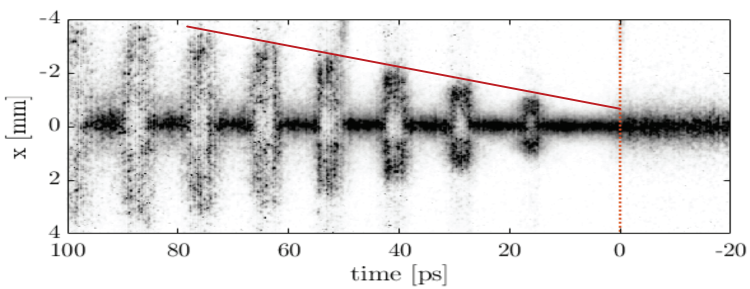
- Growth of wakefields from **increasing width of defocused protons** at the ionization front



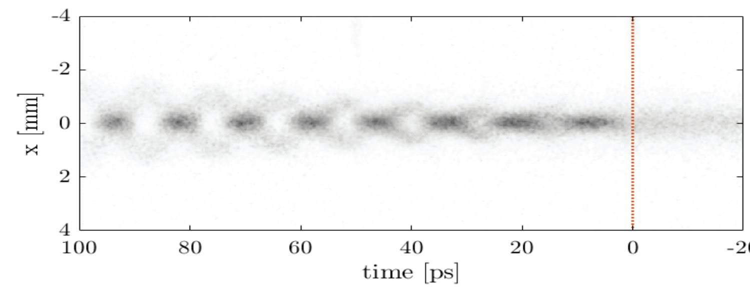
High Bunch density → High seed wakefields

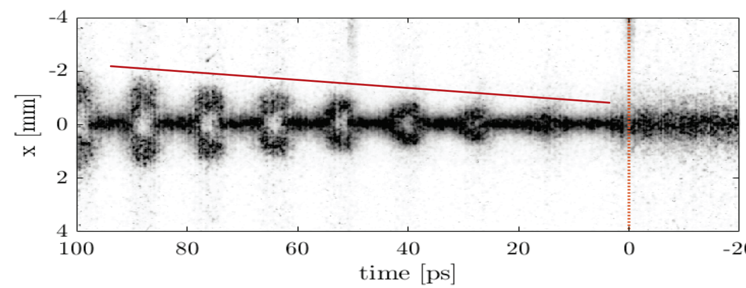
Low Bunch density → Low seed wakefields





Normalize each time slice to 1

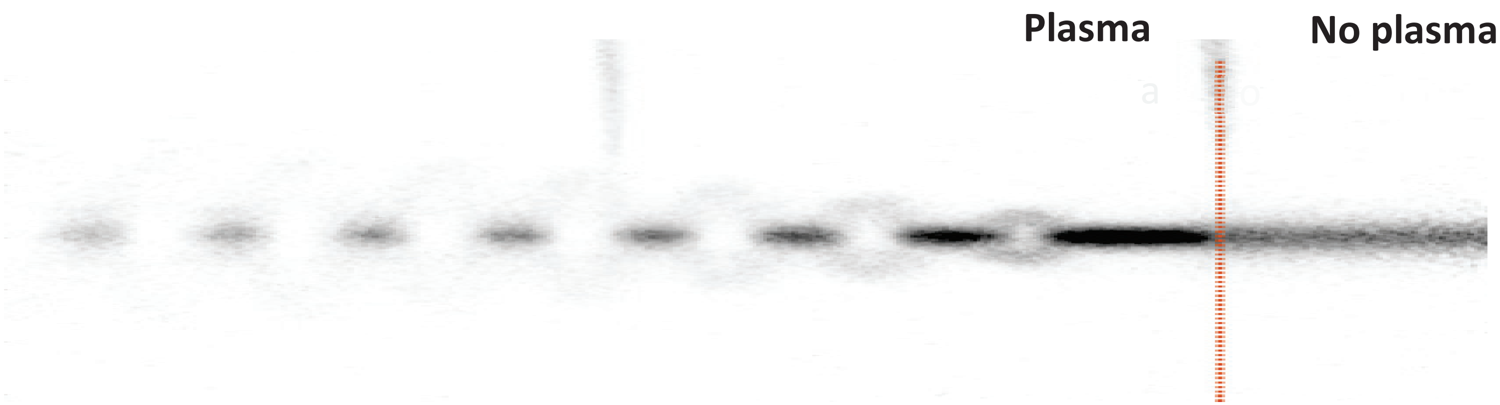




→ Wakefield growth along the bunch

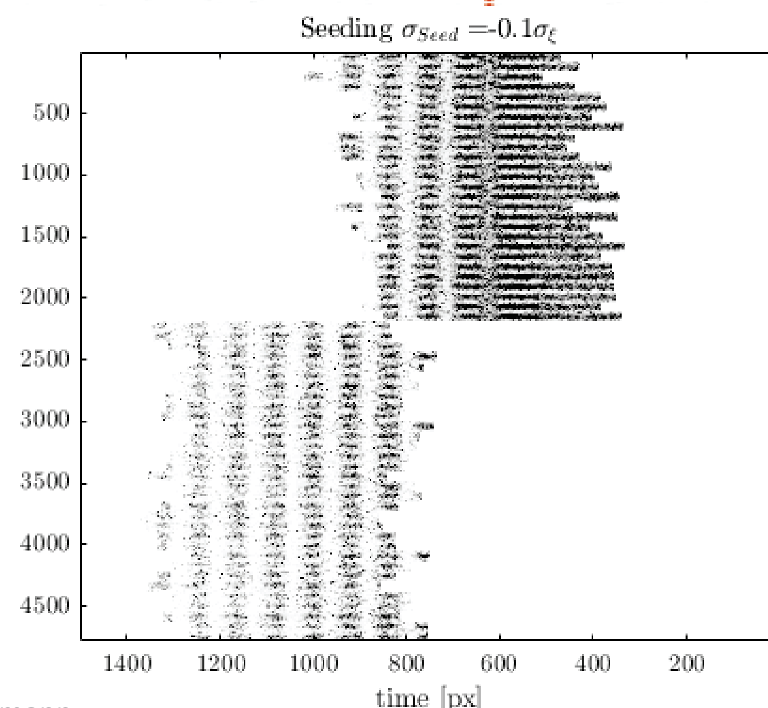
→ Changing wakefield by changing bunch density (thus seed wakefield)

Diagnostic for Self-Modulated Proton Bunch
Streak camera for Optical Transition Radiation (OTR)

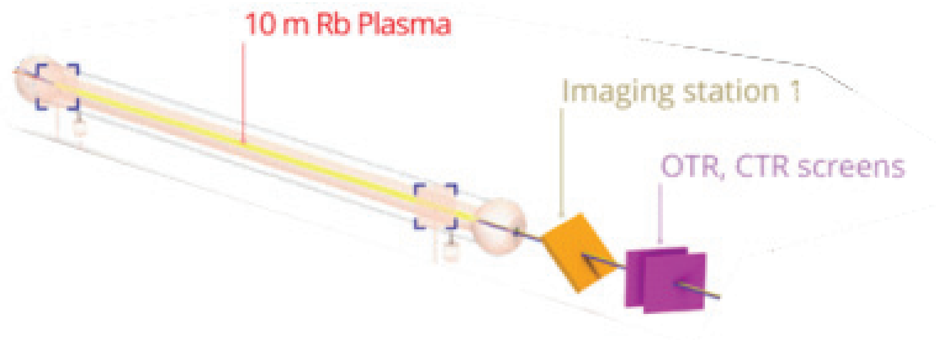


Determination from streak camera images of

- **Phase reproducibility from event to event**



Diagnostic for Self-Modulated Proton Bunch
Heterodyne Receivers for Coherent Transition Radiation (CTR)



Signal:

$n_{pe} \approx 8.4 \cdot 10^{14} cm^{-3} \rightarrow f_{pe} = f_{RF} \approx 260\ GHz$

Reference:

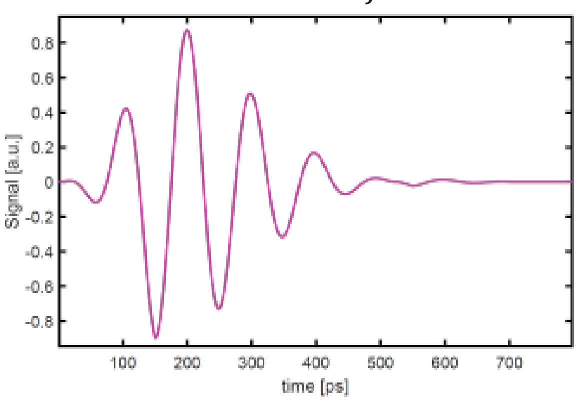
$f_{ref} \approx 270\ GHz$

Mixer

Intermediate frequency:

$\rightarrow f_{if} \approx 5 - 20\ GHz$

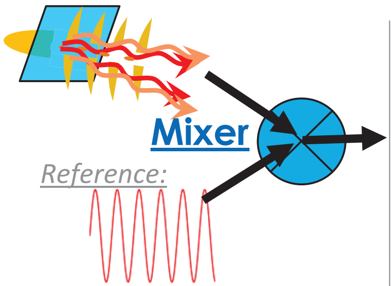
Expected signal ($f_{if} = 10\ GHz$)

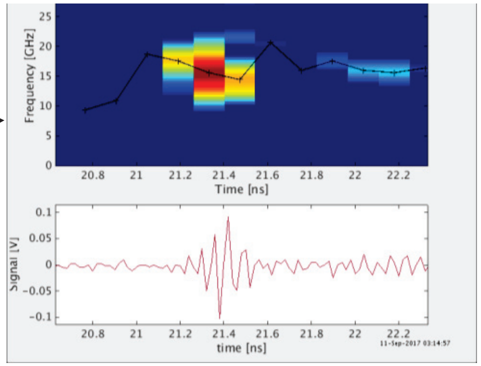


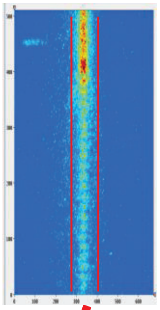
→ Analyse FFT of beating signal

→ Frequency determination of beating signal

Diagnostic for Self-Modulated Proton Bunch
Comparison of OTR and CTR results



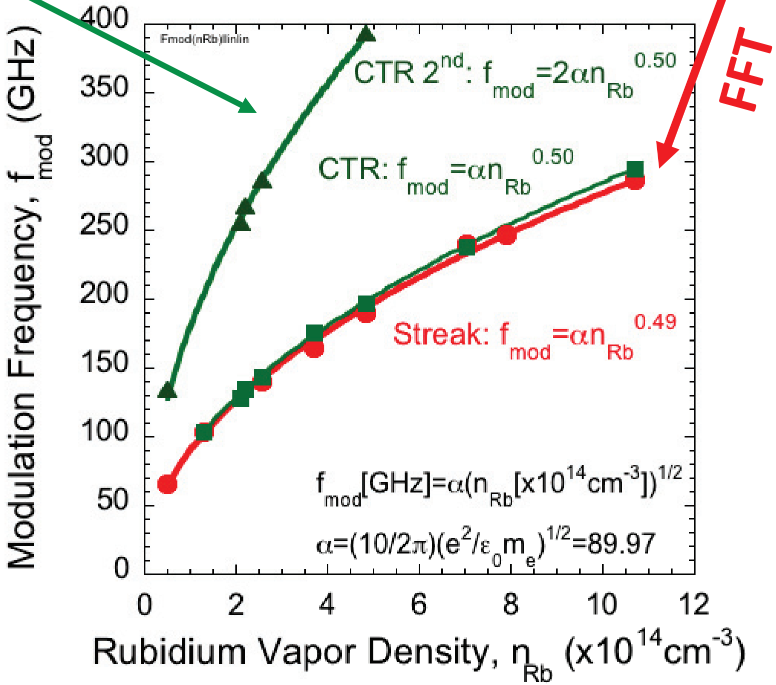




Precisely matching expected plasma frequency (vs. measured vapour density)

$f_{mod} \sim f_{pe}\ (n_{pe} = n_{Rb})$

➔ Self-Modulation with expected frequency

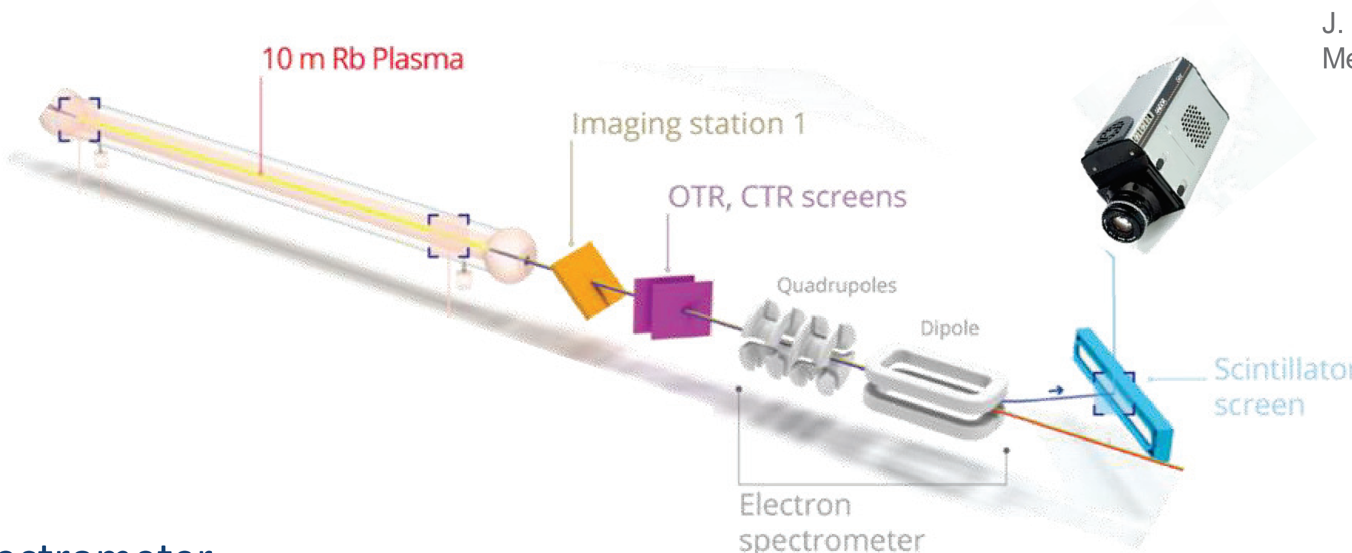


electron plasma density n_{pe}

$$\textit{Plasma frequency: } \omega_{pe} = \sqrt{\frac{n_{pe} e^2}{\varepsilon_0\, m_e}}$$

Electron Bunch Diagnostics

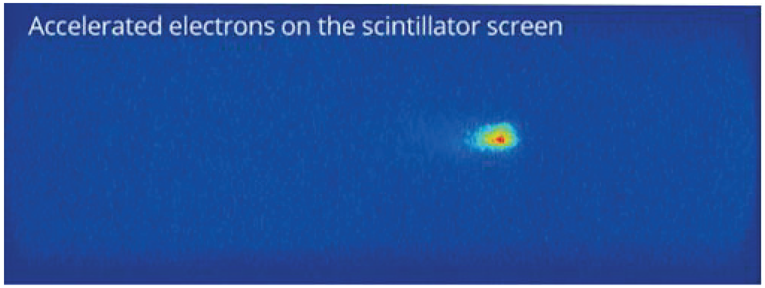
J. Bauche *et al.*, Nucl. Instr. and Meth. in Phys. Res. A, **940** (2019)



Spectrometer

- Bending angle of particles induced by dipole depending on their energy

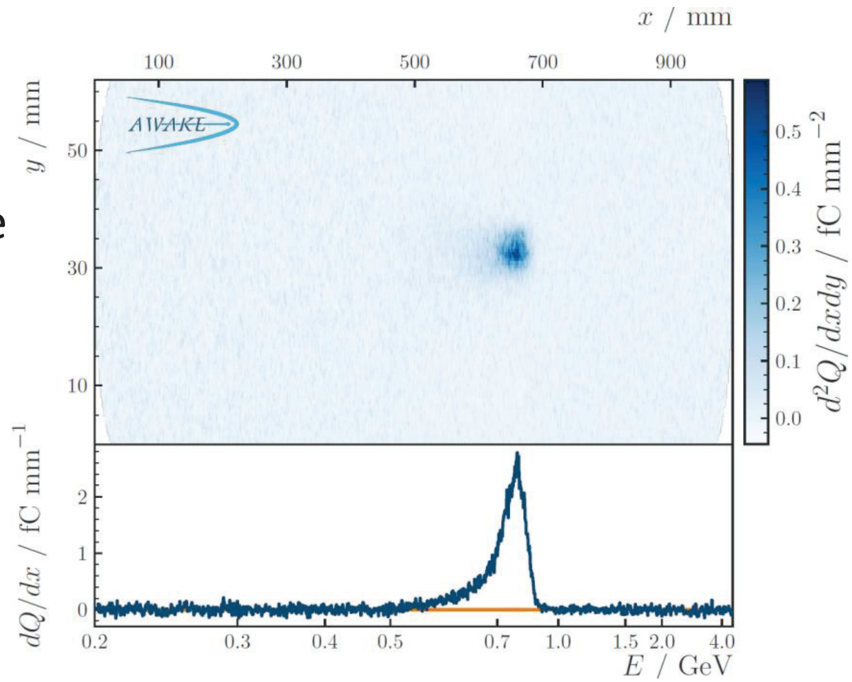
→ Position on screen gives
  - **Peak energy**
  - **Energy distribution**
- With light calibration: **Charge (capture rate)** determination
- **Emittance** measurements with quadrupole scan

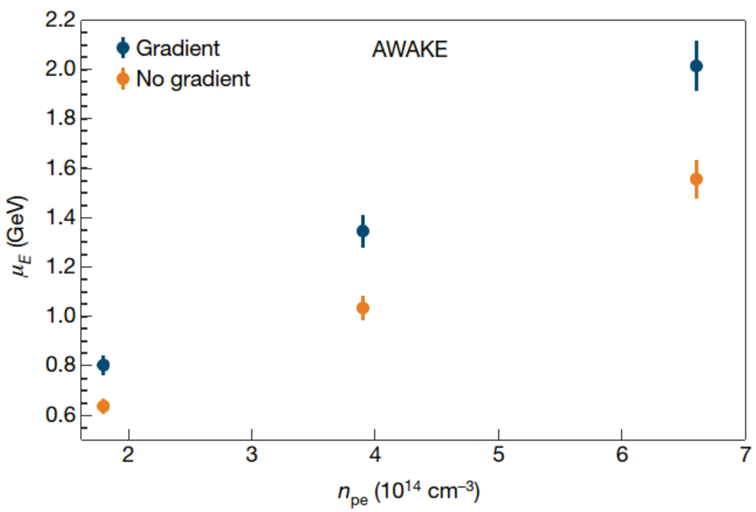


Diagnostic for Accelerated Electron Bunch Spectrometer for Energy Measurements

E. Adli et al. (AWAKE Collaboration), Nature 561, 363–367 (2018)

- **Acceleration of e^{-}s with p^{+}-driven PWFA: up to 2GeV** (injected ~19MeV)
- Narrow energy-distribution
- Varying the electron energy by varying the plasma density





Summary & Conclusions

AWAKE develops the first p⁺-bunch driven wakefield accelerator

- **Proved** the concept of the **seeded self-modulation +**
- **Injected and accelerate electrons** up to 2GeV over 10m

Diagnostics used for the self-modulated proton bunch

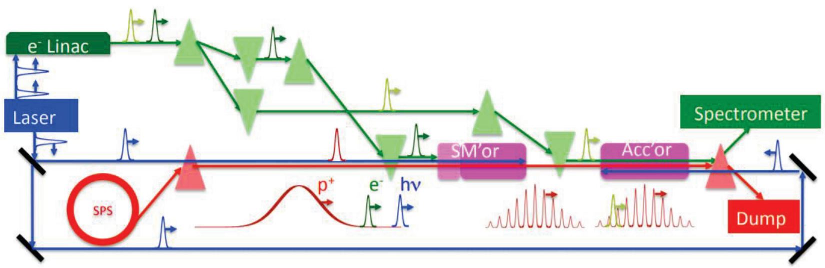
- **Two screen measurements** for **defocused protons**
- **OTR** with streak camera for **frequency determination, phase reproducibility and** characterization of **defocused protons and micro-bunches** (and other potential instabilities)
- **CTR** with heterodyne system for **frequency** determination

Diagnostics for accelerated electron bunch

- **Spectrometer** for **energy**, **energy spread**, **charge** and **emittance** determination

Future diagnostics for accelerated electron bunch

- **Bunch length** with electro-optic sampling or CTR interferometry
- **Alignment** (in the presence of the two bunches) cherenkov diffraction (electrons) beam position monitors (BPMs)
- **Emittance** with butterfly method or betatron radiation



P. Muggli, accepted for publication in Journal of Physics: Conference Series 224 (JPCS) and arXiv:1911.07534v2

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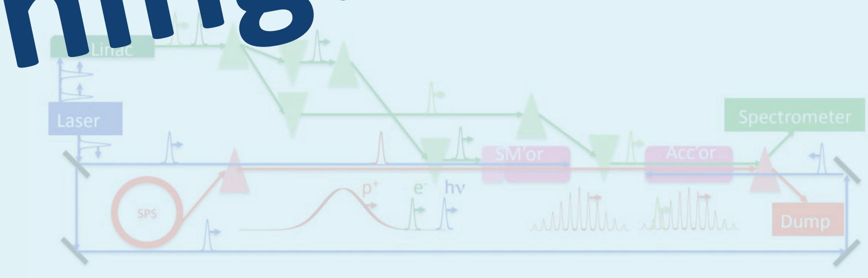

Thank you for listening!