Time resolved diagnostics in AWAKE

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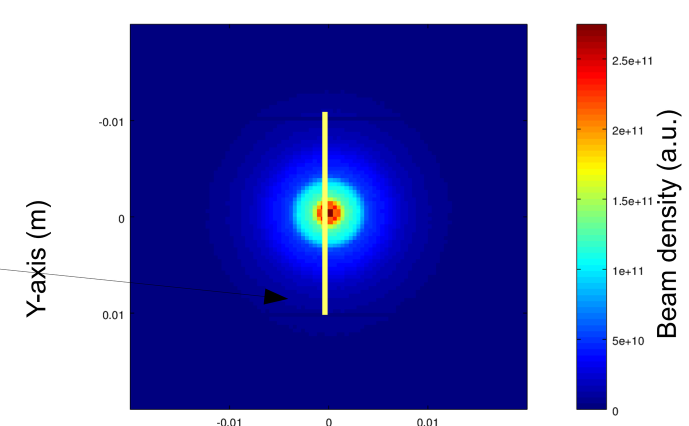
Abstract:

The AWAKE experiment relies on the seeded self-modulation (SM) of a long (ns) proton bunch in a plasma. The self-modulation of the bunch is responsible for resonant driving of the plasma wakefields and the proton bunch develops sub structures with a scale on the order of the plasma wavelength (~1.2 mm in AWAKE ↔ 237 Ghz, plasma density 7e14/ccm) that scales with the square root of the plasma density. Optical Transition Radiation as prompt lightsource and a streak camera are used to image a thin slice of the beam. The resulting time resolved image contains information about the frequency of the self modulation. The diagnostics shows the relation between the SM frequency and the rubidium density and the possibility to seed the self-modulation.

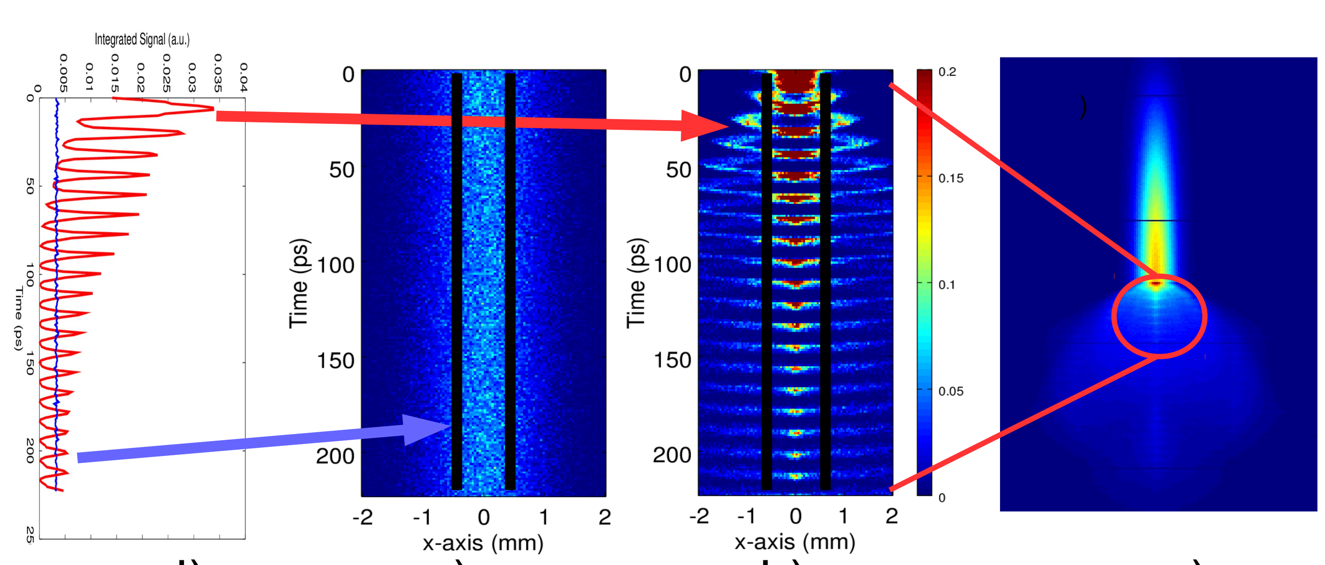
Principle:

The 400GeV SPS proton bunch for AWAKE is about 500ps long (2σ) and cannot drive wakefields resonantly. The self-modulation (SM) of the beam modulates the radial size of the beam periodically with the inverse plasma frequency as the period. Simulations show that using a hard cut bunch (using a laser to ionise in the middle/head of the bunch) enhances and seeds the SM.

To detect the SM we use Optical Transition Radiation because it is prompt. We image the OTR from the proton beam on a steak camera. The camera entrance slit (20µm) cuts out the central part of the beam. Along the slit we get a time resolved image of the beamslice.

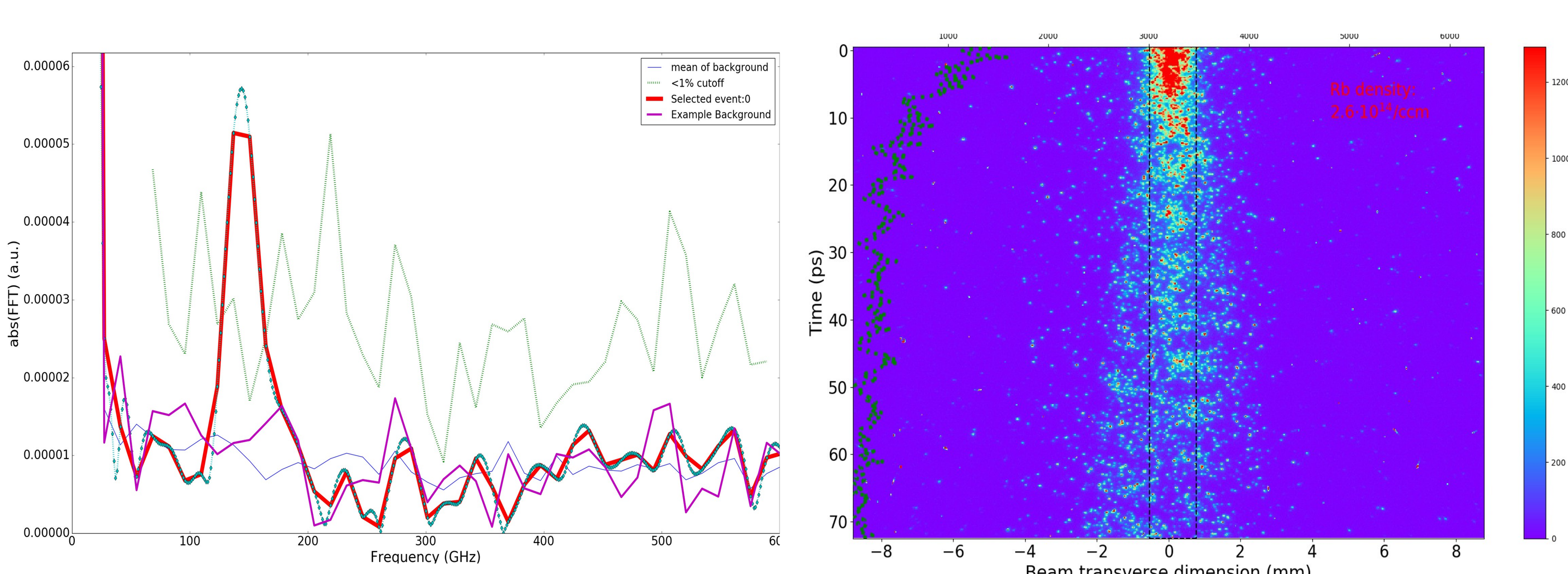


On a long timescale on the streak camera we expect to see the blown out bunch behind the laser (image a). When zooming in we expect to see a train of microbunches behind the laser (image b) compared to the image without the laser (image c). The profiles (image d) show that the detected current is modulated with the plasma frequency as modulation frequency. (Simulation results by Alexey Petrenkov, using LCODE)



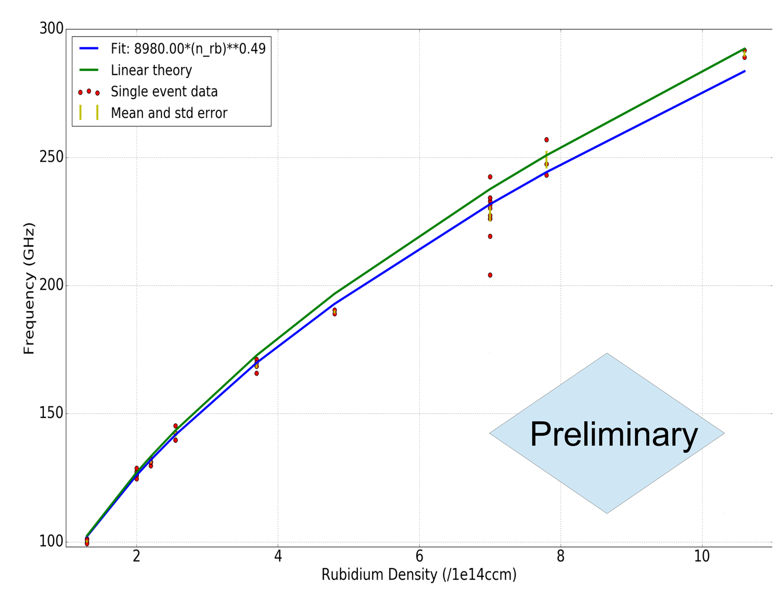
d) c) b) a)

Experiments:



a) b)

For low frequencies the FFT of the profile (image a) of the streak image with visible modulation (image b) shows a peak at the Rubidium density. The blue curve on image a) is the mean of 9 background shots without laser or Rubidium, while the purple curve shows a typical spectrum for a background event. For higher frequencies where it is no longer clear whether there is a frequency or not we use the green curve as a cutoff to detect a frequency. The cyan line with marked diamonds is used to interpolate the exact detected frequency.



We detect the frequency for different Rubidium densities and then fit

$$f = 89.80 \times \left(\frac{n_{rb}}{10^{14}}\right)^{\alpha}$$

(we assume that the ionisation rate is 1).

The resulting fit gives

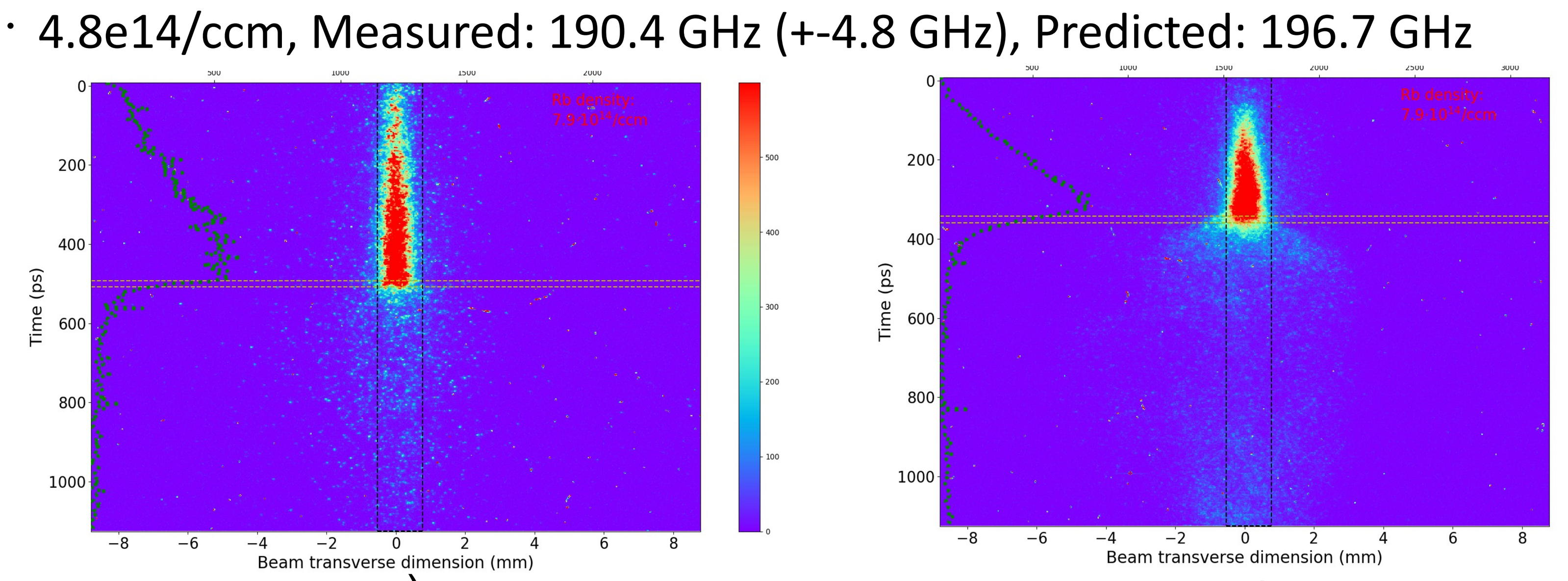
α=0.49 +- 0.01

Which shows that the frequency scales with the square root of the Rubidium density.

When the laser is put in the middle of the bunch (image a, the yellow lines give an estimated bracket for the laser position) the second half of the bunch is blown out. When placing the laser earlier in the bunch (image b) the same blowout happens to the bunch at the position of the laser. This shows that we can seed the self-modulation by creating the plasma with the laser within the bunch.

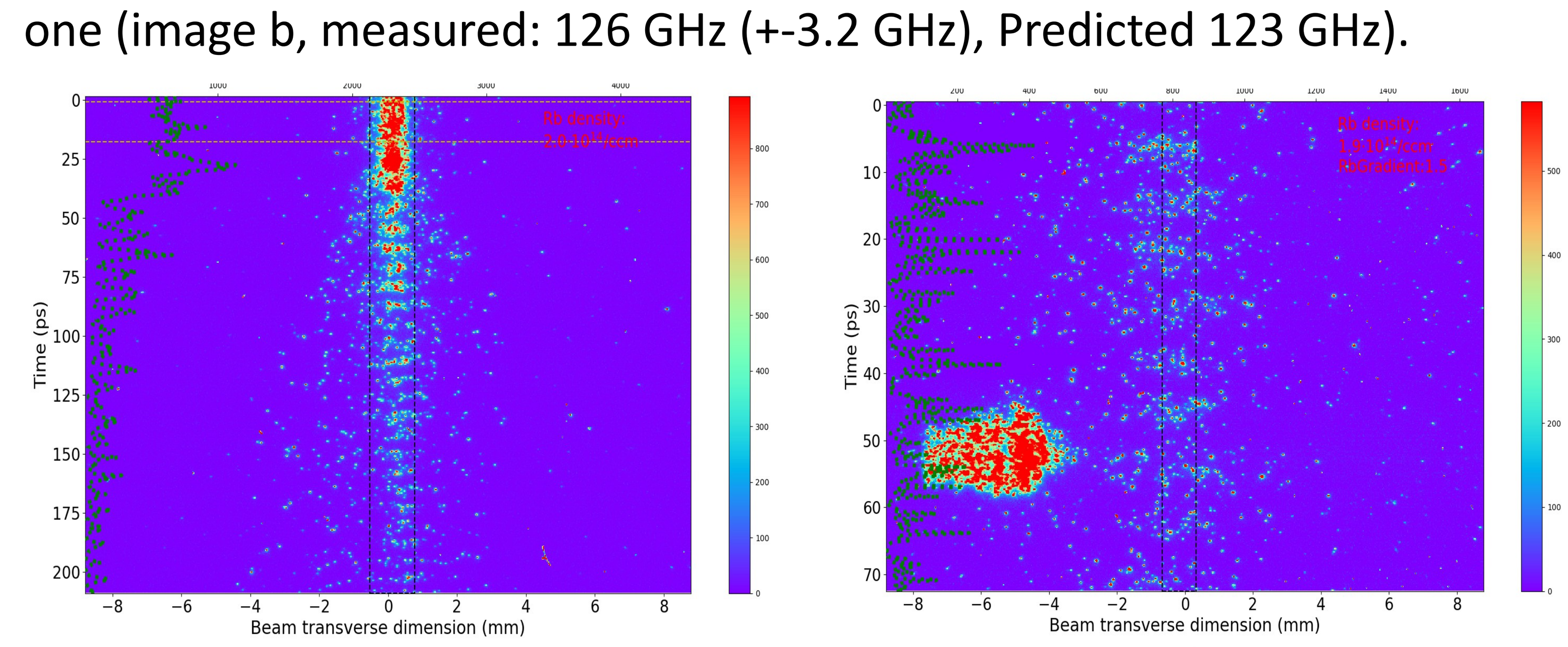
We measured the frequency after the blowout for two densities (2.2e14/ccm and 4.8e14/ccm) when placing the laser in the front of the bunch. The detected frequencies of the beamlets are within what the linear theory predicts:

- 2.2e14/ccm, Measured: 132.2 GHz (+-3.3 GHz), Predicted: 133.2 GHz
- 4.8e14/ccm, Measured: 190.4 GHz (+-4.8 GHz), Predicted: 196.7 GHz



a) b)

The lower figure a) shows that the modulation exists for at least 200ps behind the seeding laser pulse. We shifted the time window of the streak camera 370 ps behind the laser pulse (image b, red lasermarker verfies delay) and still see the microbunches with a frequency near the predicted one (image b, measured: 126 GHz (+-3.2 GHz), Predicted 123 GHz).



a) b)

Conclusion:

We directly observe the result of the seeded self-modulation as the formation of p+ micro bunches with period near the inverse plasma frequency f which scales as expected $f \sim \sqrt{n_{rb}}$.

The micro-bunches are observed over a time longer than 1σ (about 250 ps) of the p+ bunch which shows full modulation of the bunch.

Further investigation is needed to understand the depth of modulation, remaining charge in the bunches and effects related to propagation from the plasma exit to the OTR screen.

Our results are corroborated by the two-screen measurements (see M. Turner's poster/talk).