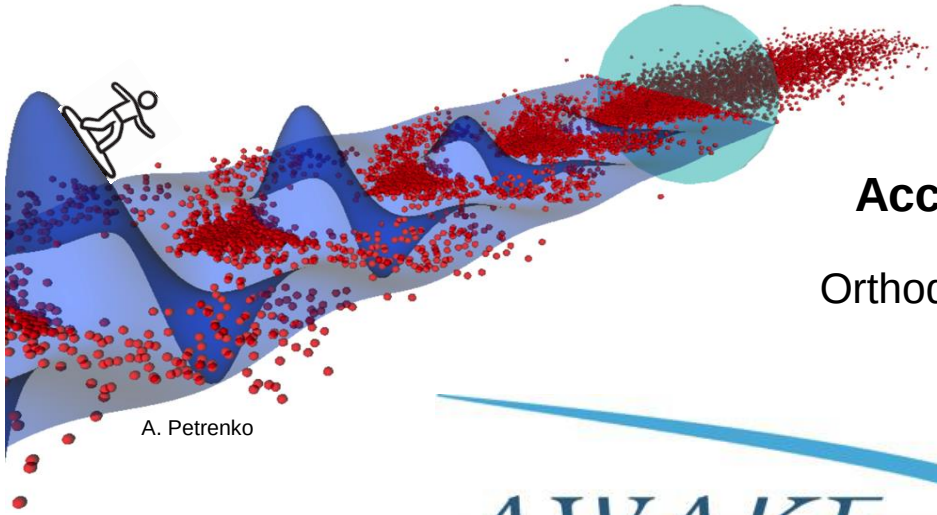
Overview and first results of the advanced acceleration experiment AWAKE at CERN

Falk Braunmueller, for the AWAKE collaboration


A. Petrenko

11 July 2018

3rd European Advanced Accelerator Concepts Workshop

Orthodox Academy of Creta (OAC), Greece

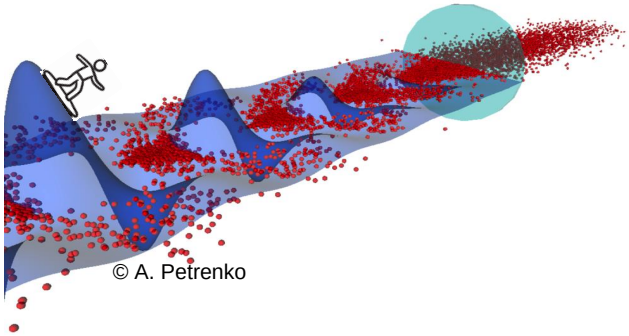
AWAKE

MAX-PLANCK-GESELLSCHAFT

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

Outline

- **AWAKE-concept: p^+-driven plasma wakefield**
- **AWAKE setup**
- **Results 1: Seeded Self-modulation**
- **Results 2: Acceleration**
- **AWAKE upgrade**
- **Future applications**



MAX-PLANCK-GESELLSCHAFT

AWAKE

Present and future colliders

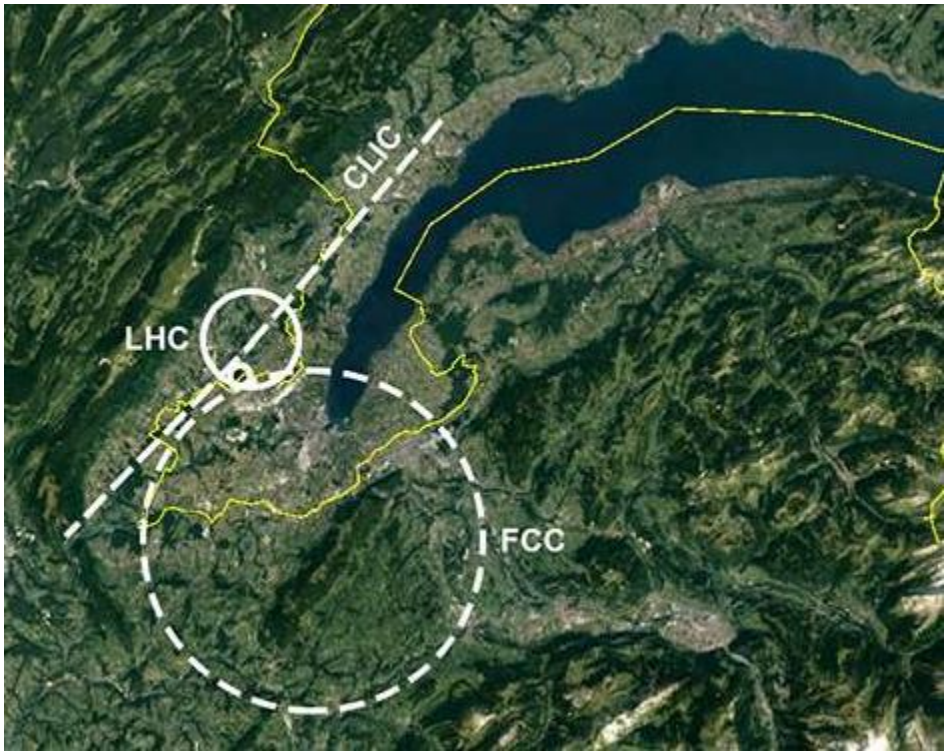
Possible future RF-driven accelerators:

~0.3-1TeV e^--e^+ or >13TeV p^+-p^+ or …

CLIC / ILC: 30-50km or FCC: 80-100km

➔ Huge cost (LHC: ~billions); very difficult to get funding

➔ Advanced accelerators → stronger acceleration → shorter accelerators



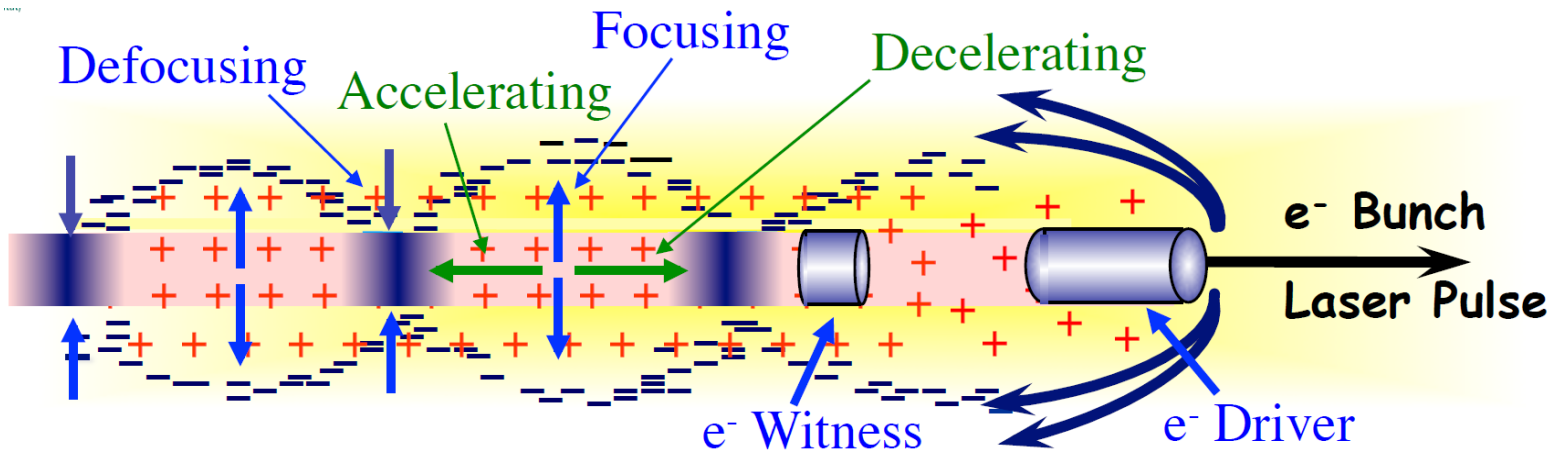
Candidates: THz-accelerators, dielectric accelerators, laser-wakefield accelerators (LWFA), beam-driven plasma-wakefield accelerators (PWFA)

AWAKE

MAX-PLANCK-GESELLSCHAFT

AWAKE

Plasma acceleration



- Overcomes break-down limitation of RF-accelerators
- Most common: Laser / e^- pushes out plasma e^-'s

→ oscillate in & out as plasma oscillation.

→ Accelerating & decelerating field

→ relativistic witness beam sees permanent acceleration

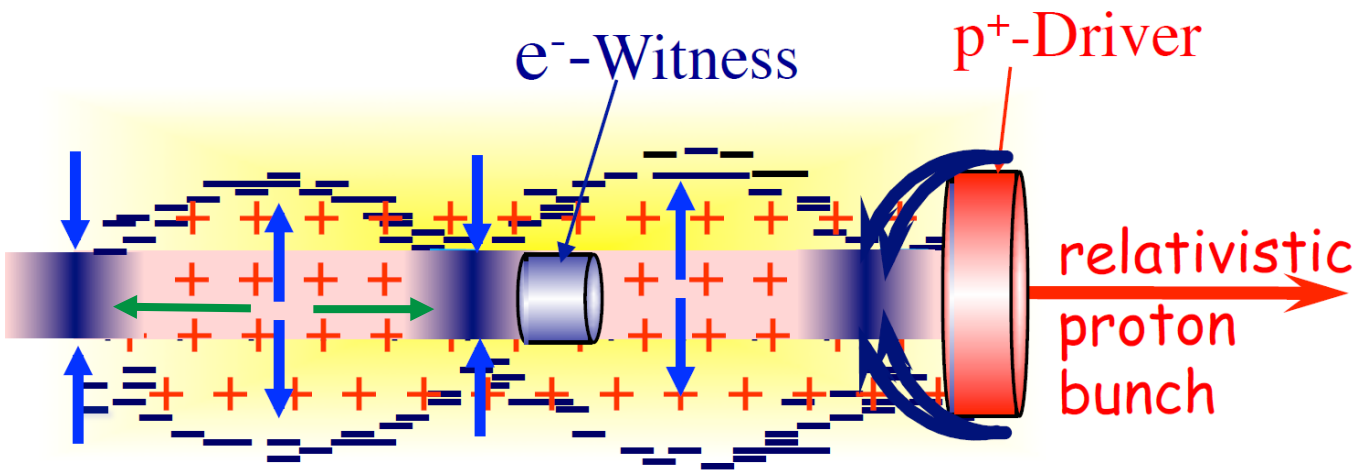
- max. field ~several GeV/m
- max. energy: large fraction of drive bunch

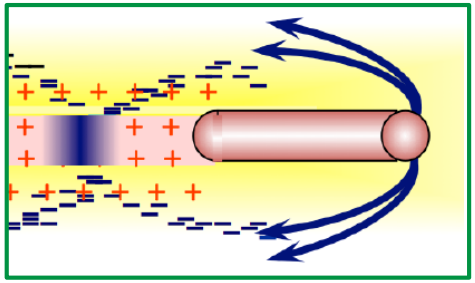
→ **staging** for high-energy electrons**?**

MAX-PLANCK-GESELLSCHAFT

AWAKE

p+-driven PWFA





- plasma electrons pulled in

→ same with different phase

- problem: short p+-bunches are not available in high quality

- **Solution: proton self-modulation**

MAX-PLANCK-GESELLSCHAFT

AWAKE

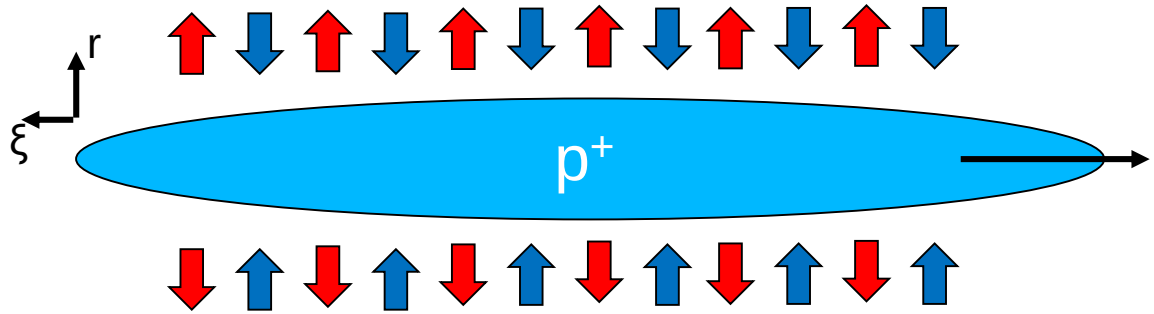
Proton bunch self-modulation

CERN proton bunch:
10-30cm long ➔ not efficiently driving wakefields for
n_{plasma}~1-10·10^{14}/cm^3
➔ λ_p~1-3mm

Radial wakefields modulate p^+-bunch with periodicity λ_p.

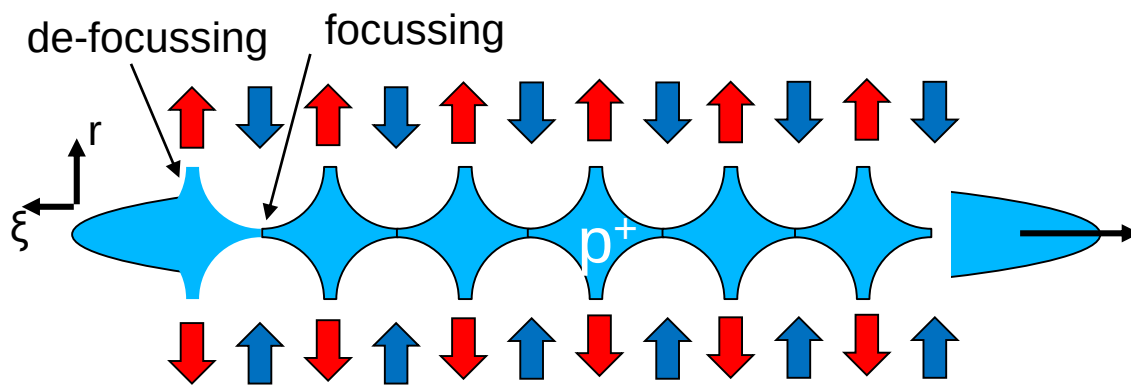
Back-coupling: higher bunch-density → stronger wakefield

➔ Resonant growth as self-modulation instability to ~GV/m (limit: wave-breaking field)



$$W_\perp(r,\xi) = -4\pi\rho_0 \int_0^\xi r_b(\xi')I_1\{k_p r(\xi')\}K_1\{k_p r_b(\xi')\}f(\xi') \times f(\xi')\, k_p \sin k_p(\xi-\xi')\, d\xi'$$

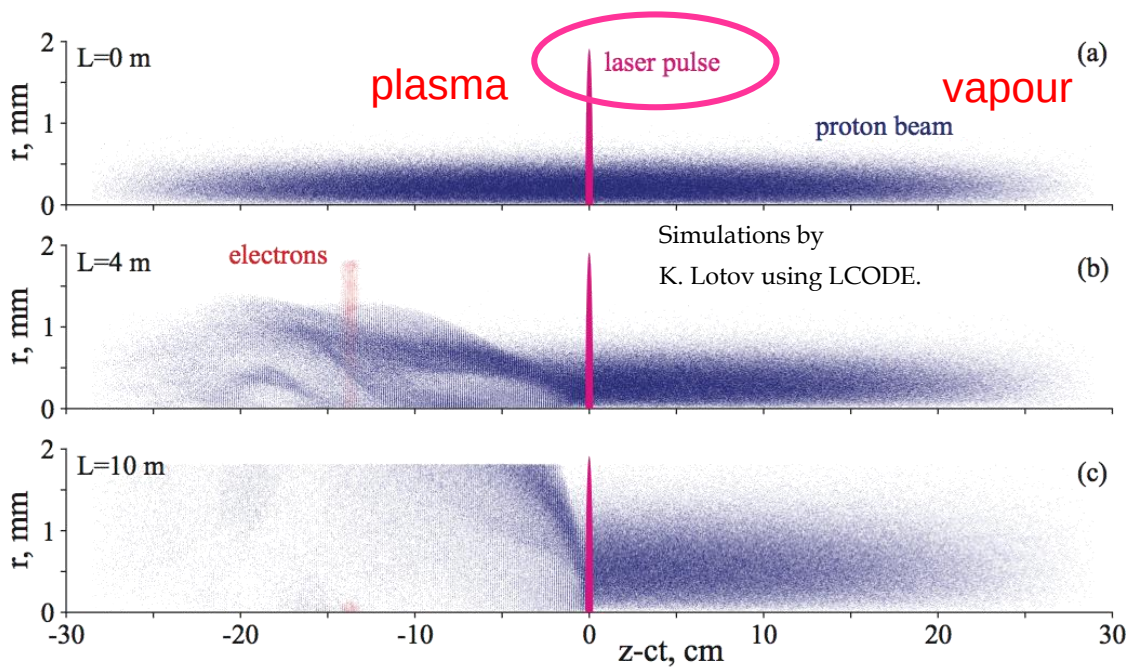
Oscillating radial force → acceleration

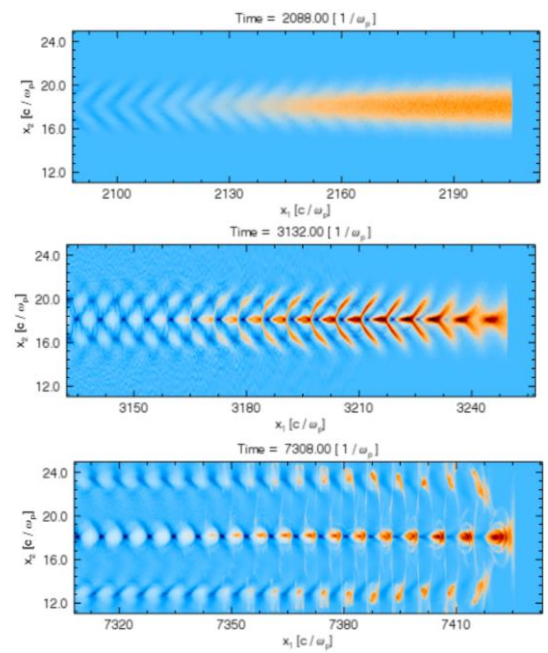


Seeded self-modulation

Behind laser:

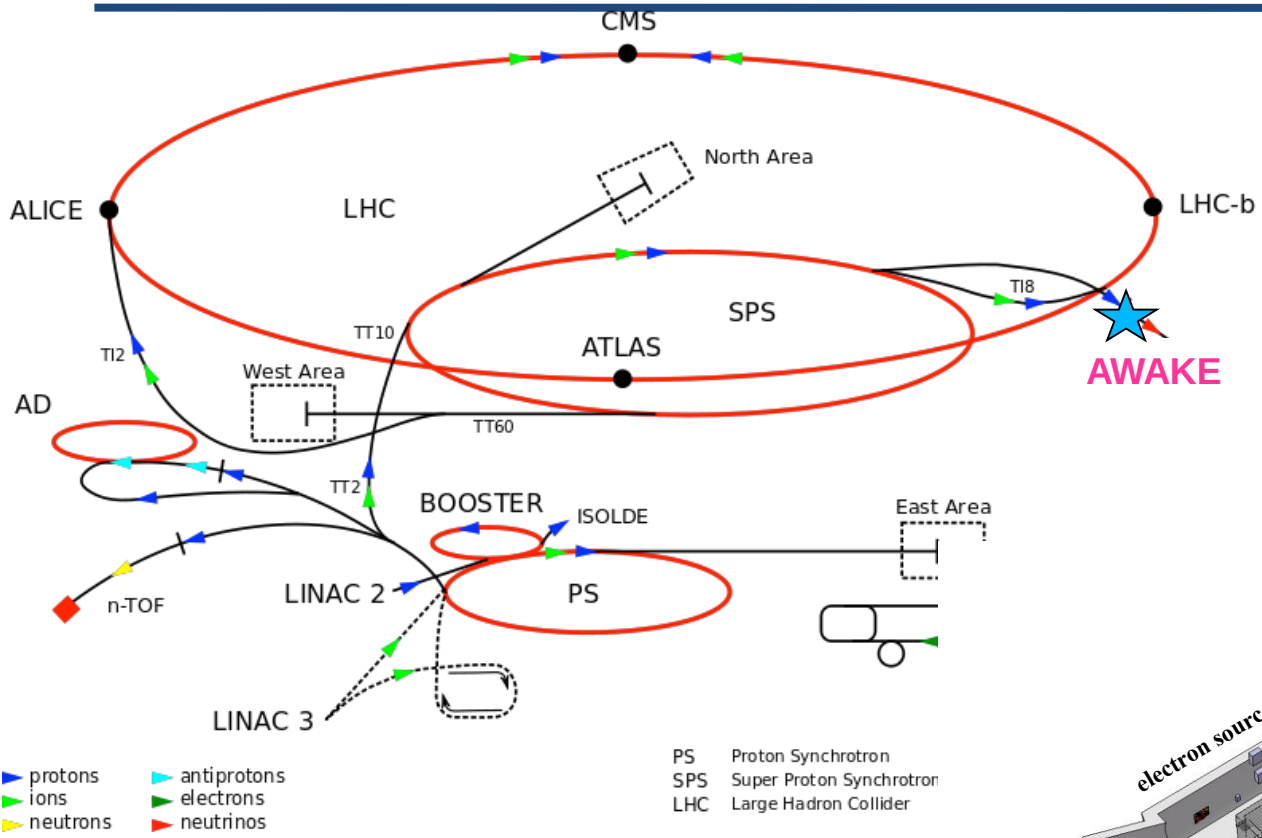
- Seed transverse wakefields modulate the bunch density with period $\sim\lambda_{pe} << \sigma_{z,\xi}$
- Resonant growth along bunch





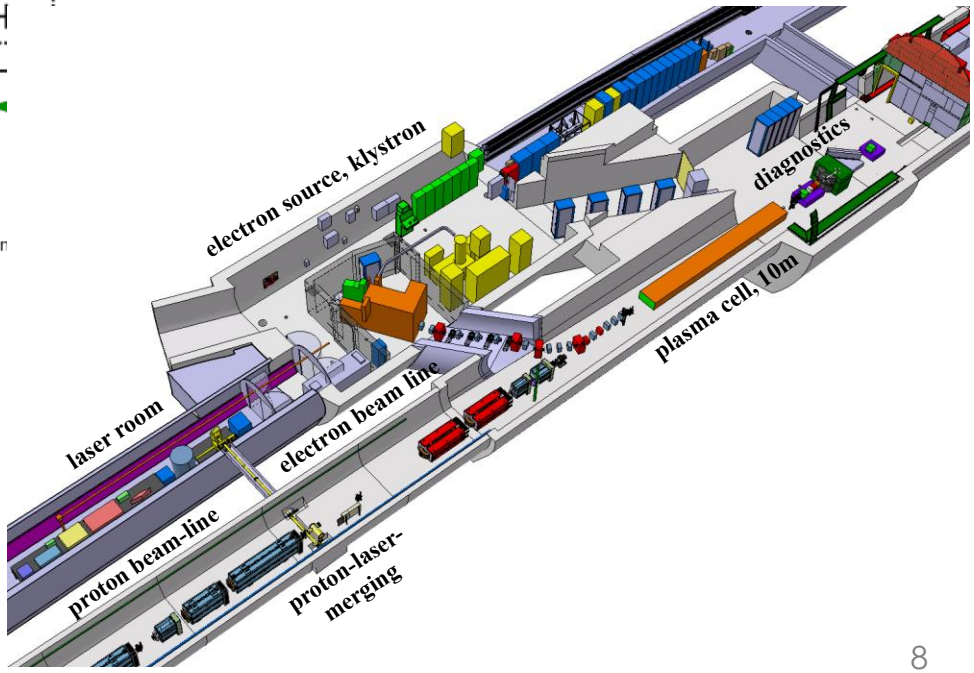
Simulations by J.Vieira using OSIRIS

AWAKE @ CERN



- SPS-proton bunch (400GeV): ~19kJ;
- LHC-bunch (13TeV): ~112kJ

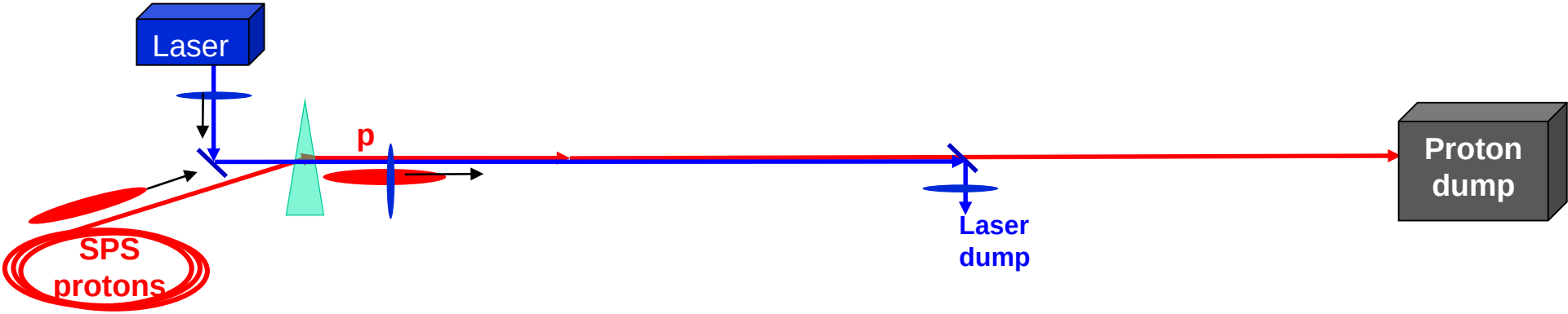
→ could accelerate a full ILC/Clic e^--bunch (~1.6kJ) in a **single stage**



SPS: 400GeV, $3 \cdot 10^{11}$ p^+,
$\sigma_r \sim 0.2$mm, $\sigma_z \sim 12$cm

➔ **self-modulation**

Experimental setup

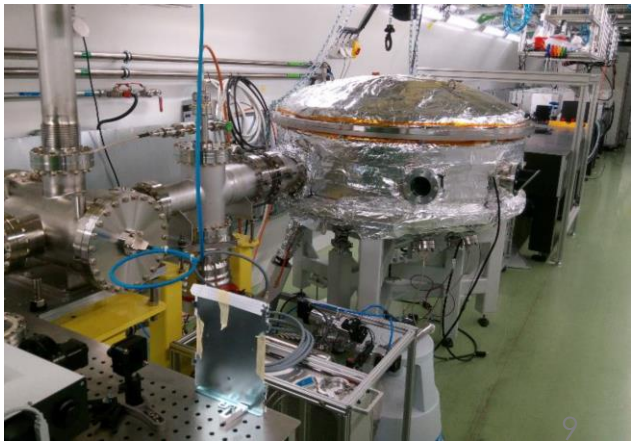


p^+ from SPS:
with chicane for merging

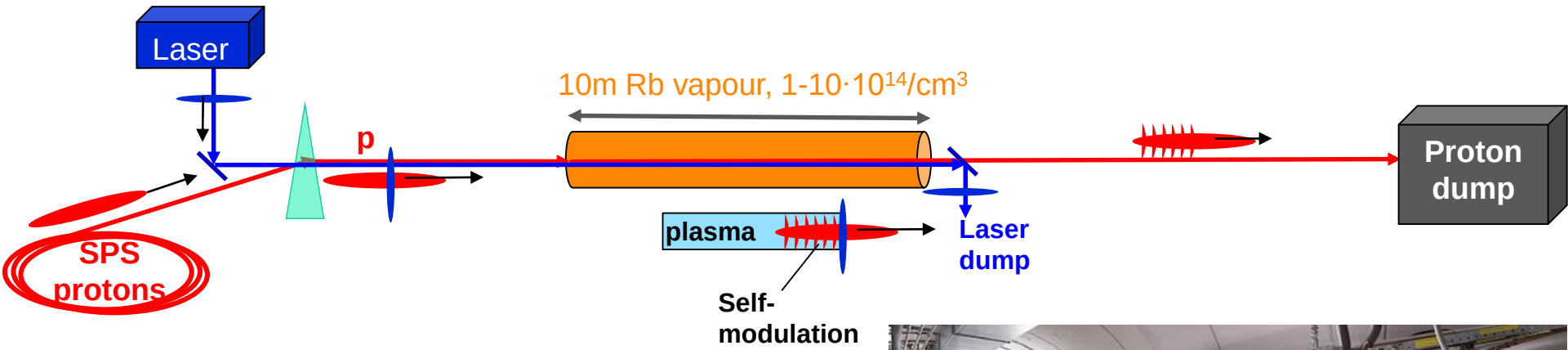
- Ionizing laser:

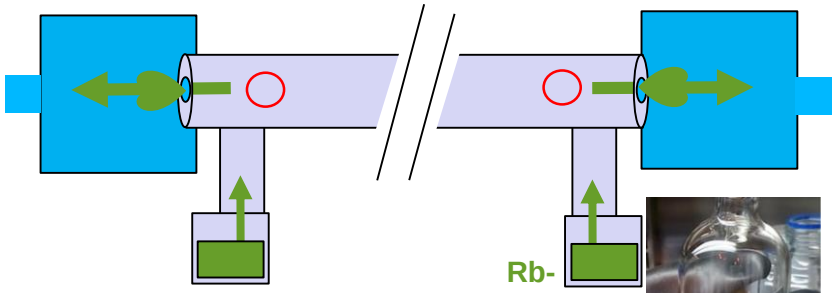
Fiber/Ti-Sapphire laser:
~100fs, E_{max}=450mJ,
$\mathbf{r_0}$**~1mm**, Z_R~5m,
I_{max}>10x10^{12}Wcm^{-2}

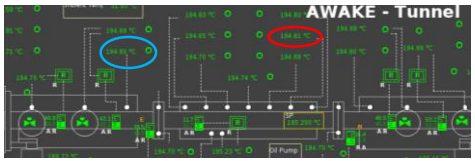
- Rb: ,I_P=4.177eV,
  I_{app}~1.7x10^{12}Wcm^{-2}
- Field ionization ➔ n_e=n_{Rb}
- Virtual line for alignment



Experimental setup







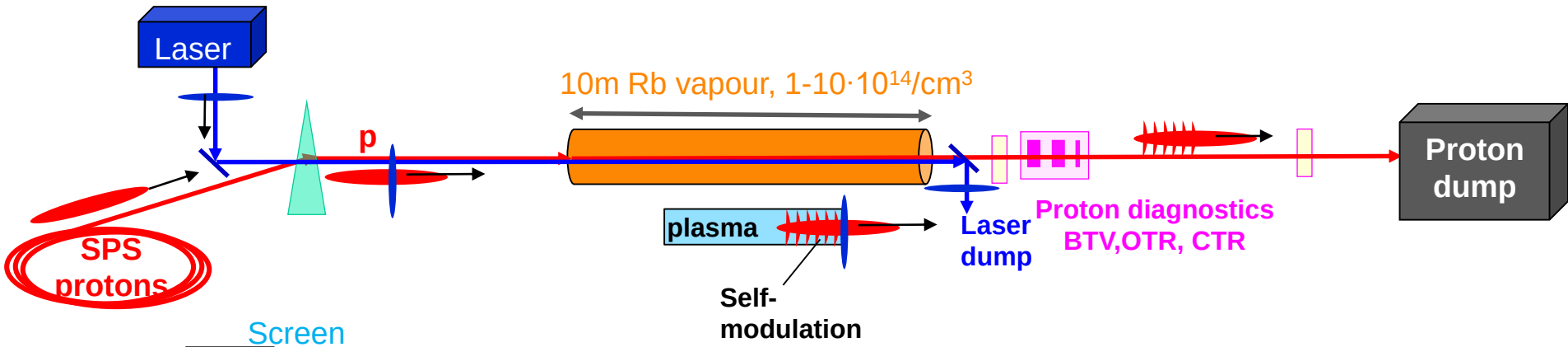
10 m Rubidium vapour cell

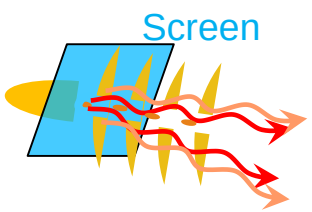
- Plasma density-requirement:
  $1\text{-}10\cdot10^{14}/cm^3$ + uniformity $\Delta n_e/n_e<0.2\%$

  ↓

  10 m oil bath, Rb @ 160-220°C
- Evaporation → flow → condensation
- Density-measurement: white-light interferometry
  ➔ accuracy <0.3%
  ➔ Gradient controlled via $T_{Rb\text{-}source}$ (<0.3%/10m)
- Beamline (ripples):
  $\Delta T/T = \Delta n_{Rb}/n_{Rb} \sim 0.15°C^{measured}/500K = 0.03\%$!!

Experimental setup



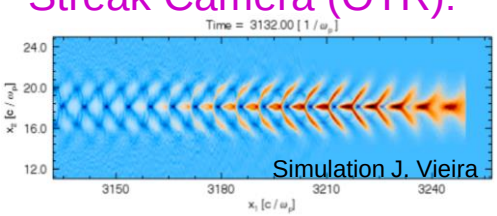


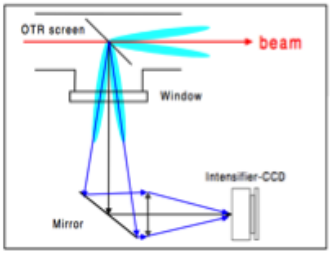
Modulated p+
→ coherent/optical TR (CTR/OTR)

CTR-diagnostics:

Coherent transition radiation @ $f_{modulation}$ (90-280GHz)

Streak Camera (OTR):





Streak Camera

≤1ps resolution

Signal:

f_{CTR} ~260GHz

Mixer

Intermediate frequency:

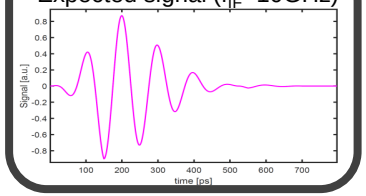
f_{IF} ~5-20GHz

Reference:

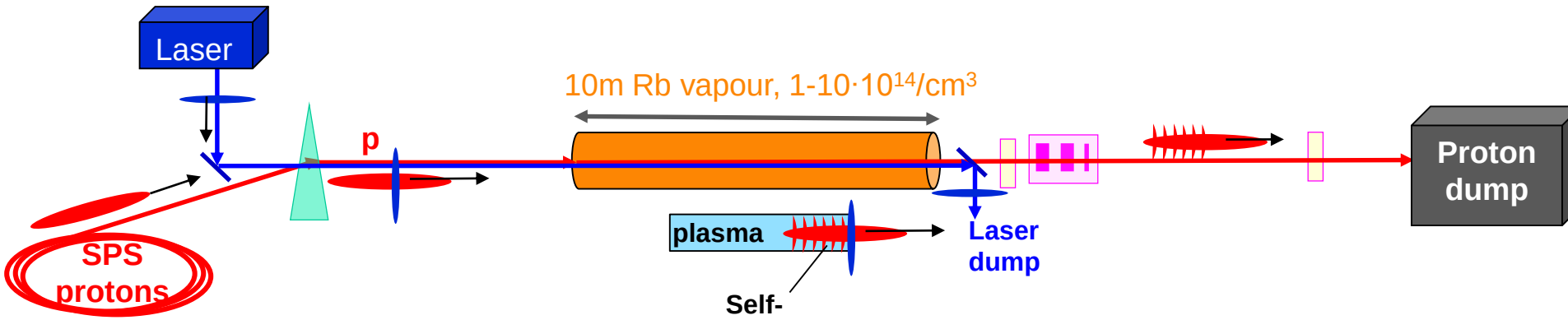
f_{ref}~270GHz

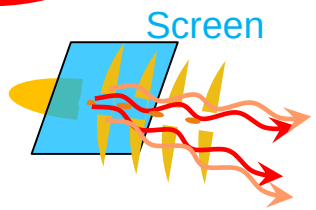
Oscilloscope

Expected signal (f_{IF}=10GHz)



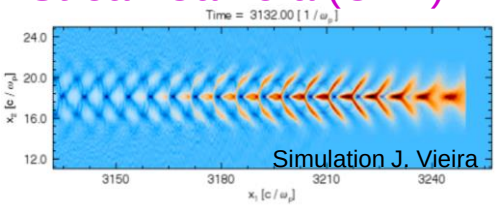
Experimental setup





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

Streak Camera (OTR):



CTR-diagnostics:

Coherent transition radiation @ $f_{modulation}$ (90-280GHz)

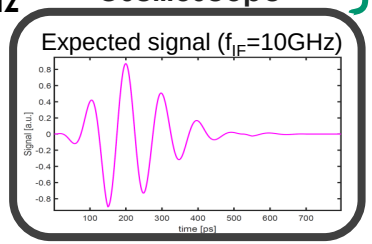
Signal:
f_{CTR} ~260GHz

Mixer

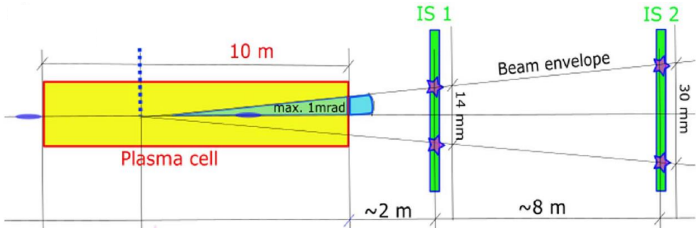
Reference:
f_{ref}~270GHz

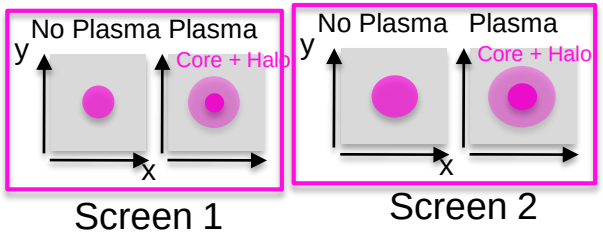
Intermediate frequency:
f_{IF} ~5-20GHz

Oscilloscope



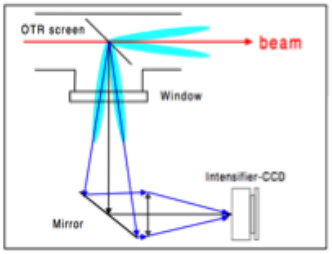
2-screen BTV:



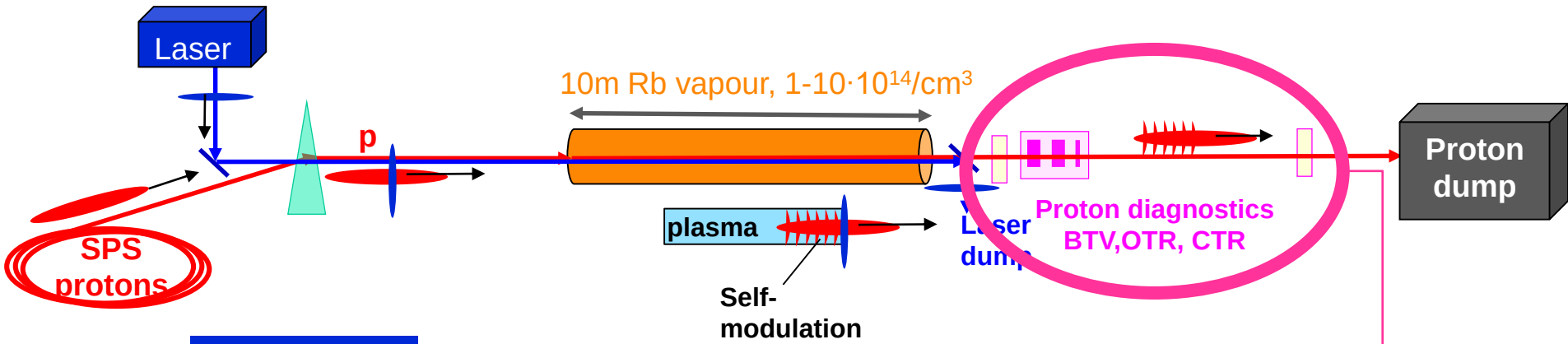


Streak Camera

≤1ps resolution



1st AWAKE-goal: SSM



2016-17

- **1st goal: Demonstrate Seeded Self-Modulation of a long proton bunch: $\sigma_z >> \lambda_{pe} \sim n_e^{-1/2}$**
- Diagnostics: Screens + OTR on streak camera + CTR
- Observables: Defocused protons + bunch-profile + modulation-frequency

MAX-PLANCK-GESELLSCHAFT

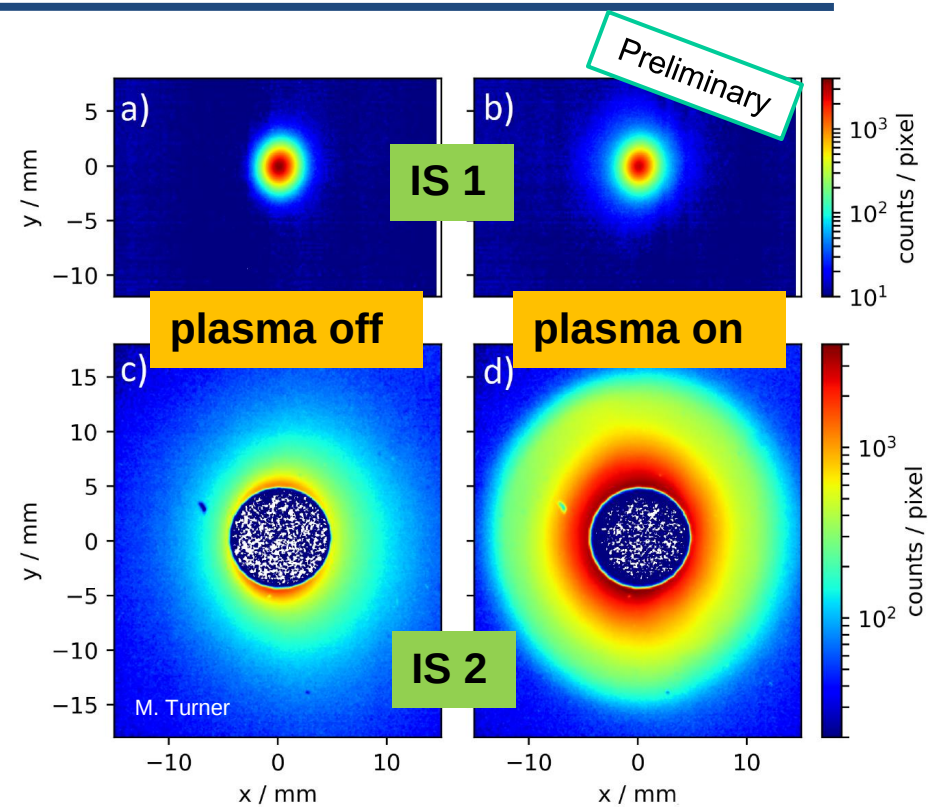
AWAKE

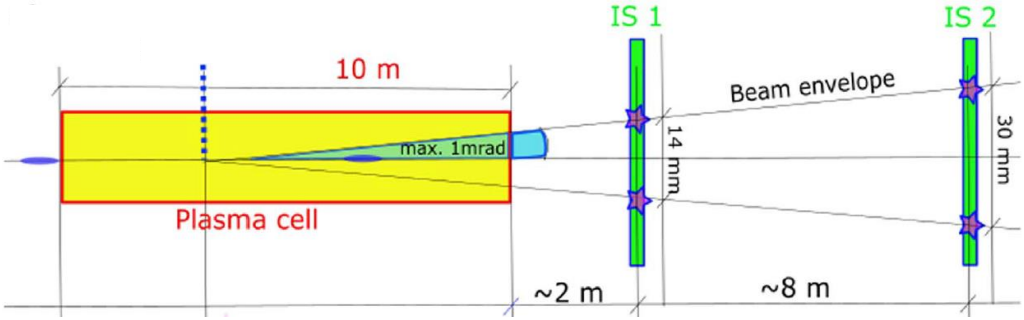
1st AWAKE-goal: SSM

Two-screen BTV:

- Defocused p^+s with plasma

➔ strong defocussing fields from wakefields inside plasma

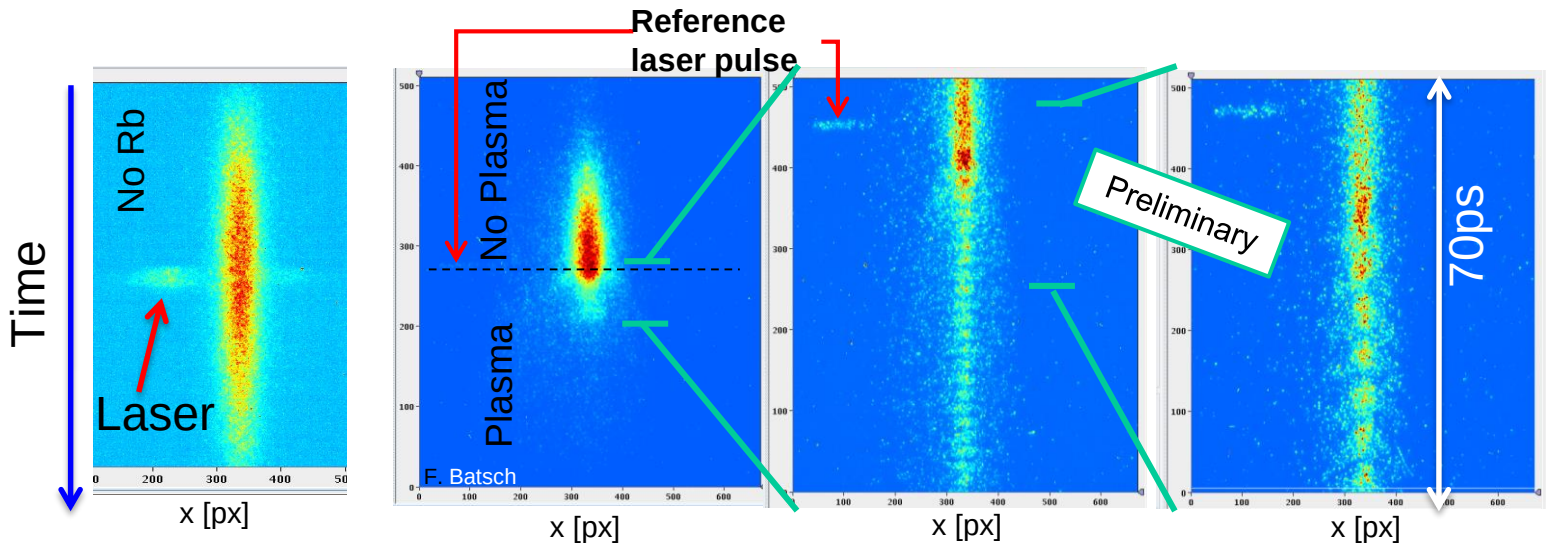




1st AWAKE-goal: SSM

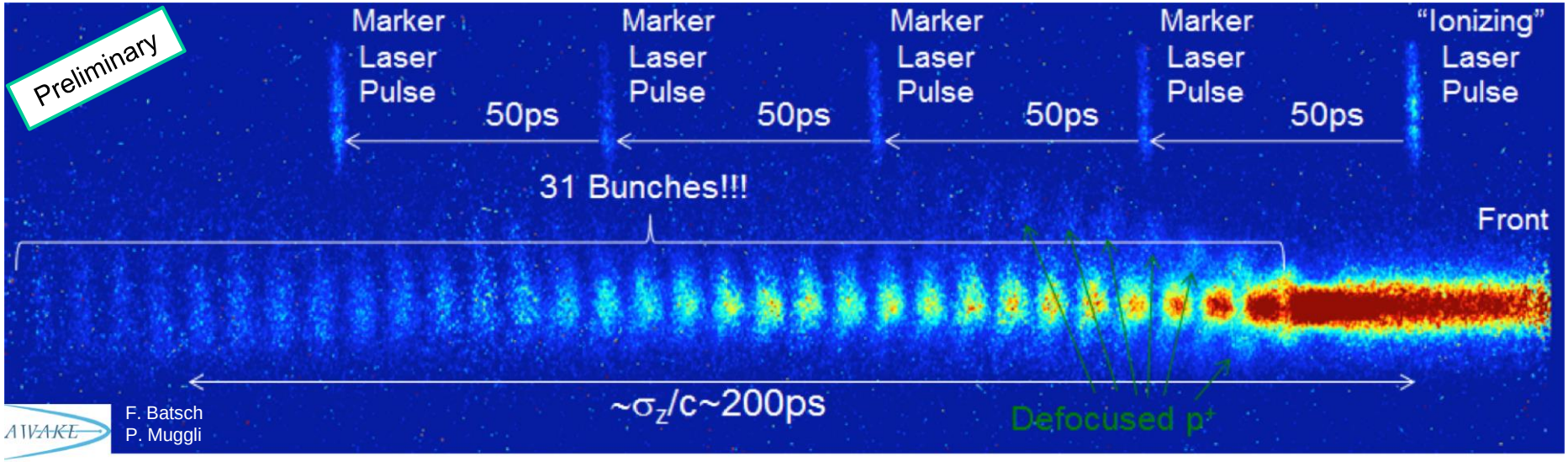
OTR on streak camera:

- Time-structure of self-modulation: Defocused + microbunches
- Seeding → SSM with phase stability



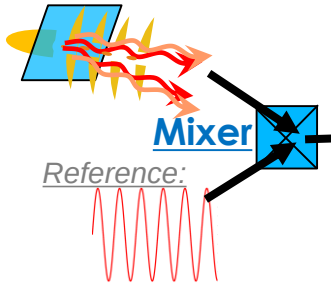
1st AWAKE-goal: SSM

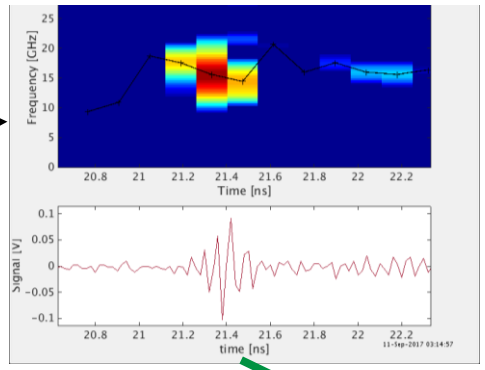
- Microbunches reach all the way along p^+-bunch! (good for e^- acceleration)
- Overlayed pictures ➔ Very phase-stable & reproducible!!

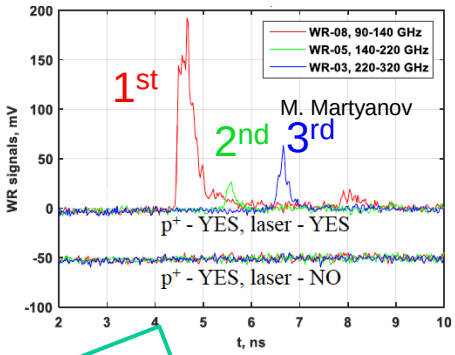


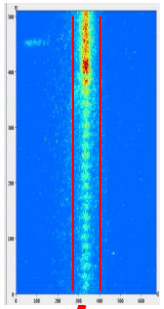
MAX-PLANCK-GESELLSCHAFT

1st AWAKE-goal: SSM









Preliminary

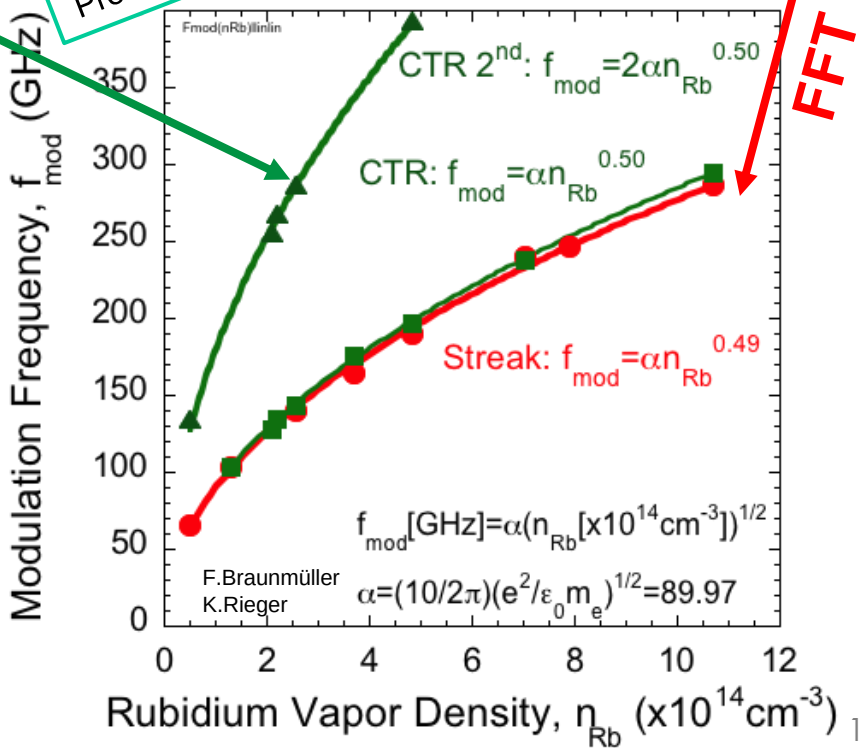
FFT

CTR and OTR frequency measurement:

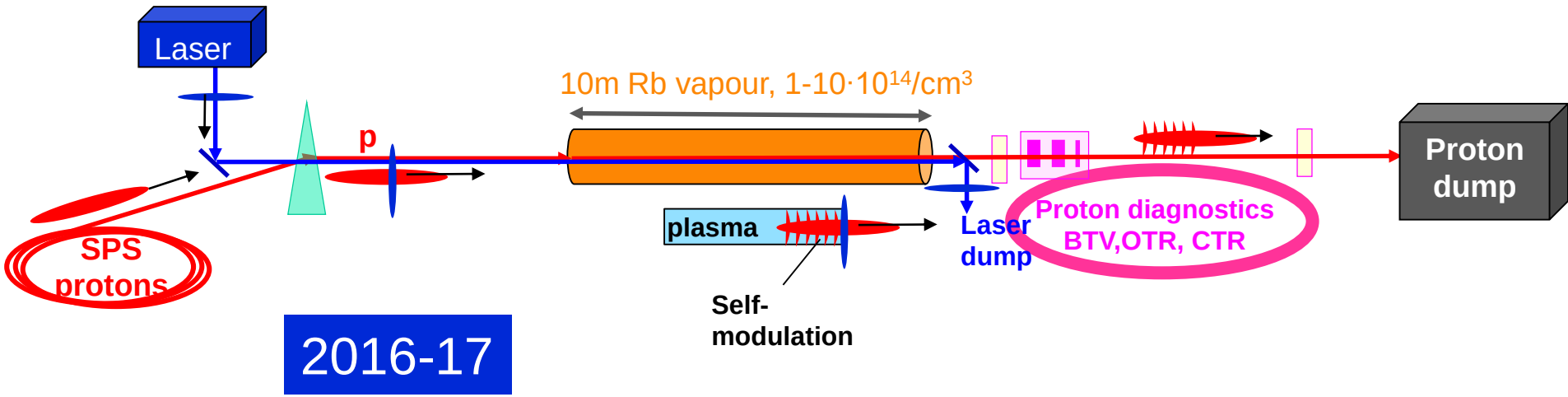
- Precisely matching expected plasma frequency (vs. measured **vapour** density)
  $f_{mod} \sim f_{plasma}(n_{Rb})$

➔ ~100% singly ionized Rb-plasma

➔ SSM with expected behaviour



1st AWAKE-goal: SSM

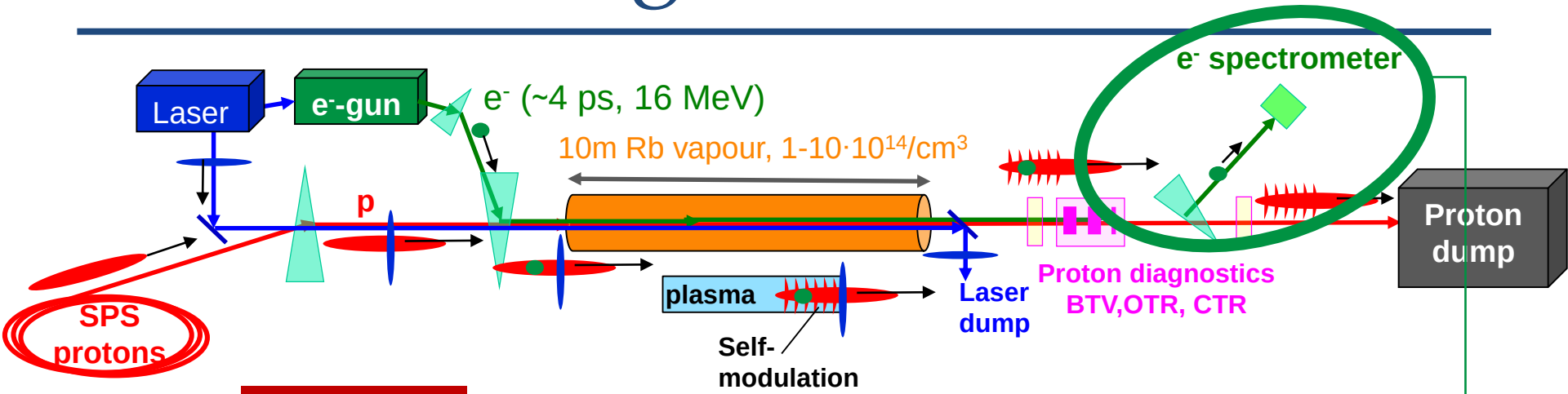


- 1st goal: show Seeded Self-Modulation of a long proton bunch: $\sigma_z >> \lambda_{pe} \sim n_e^{-1/2}$ ✓
- Diagnostics: Screens ✓ + OTR on streak camera ✓ + CTR ✓
- Observables: Defocused protons ✓ + bunch-profile ✓ + modulation-frequency ✓

MAX-PLANCK-GESELLSCHAFT

AWAKE

2nd AWAKE-goal : e⁻-acceleration

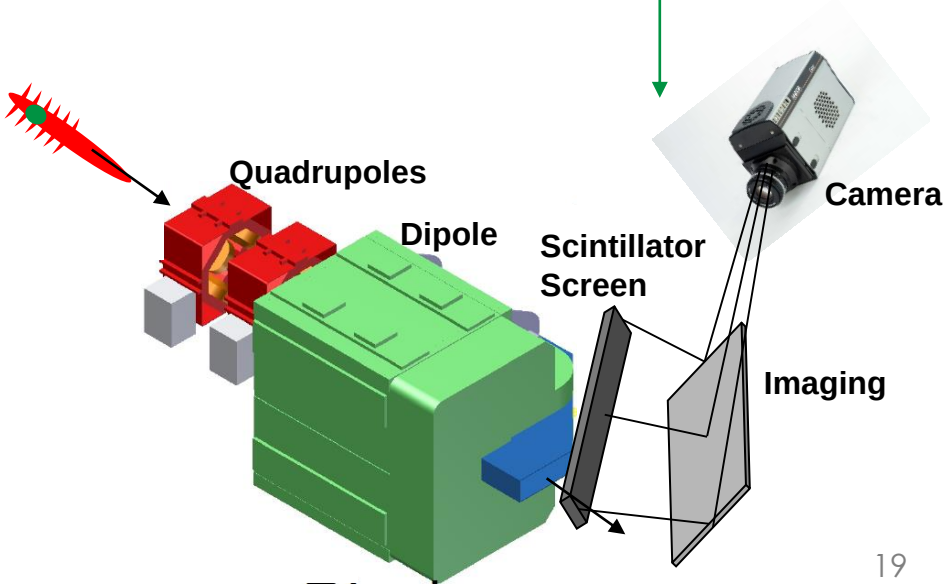


2017-18

- 3 beams overlapped & synchronized with picosecond-precision: p^+ + laser + e^-

- Diagnostics:

  Electron spectrometer



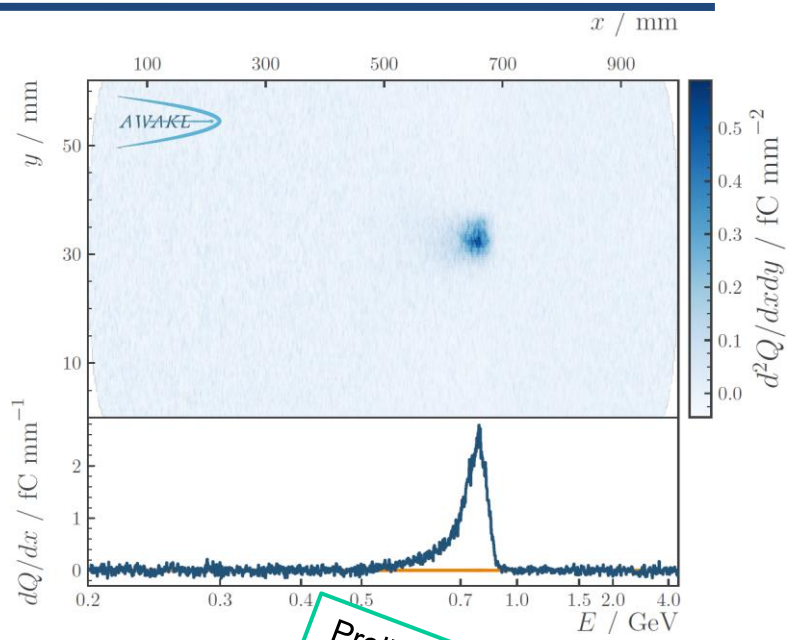
MAX-PLANCK-GESELLSCHAFT

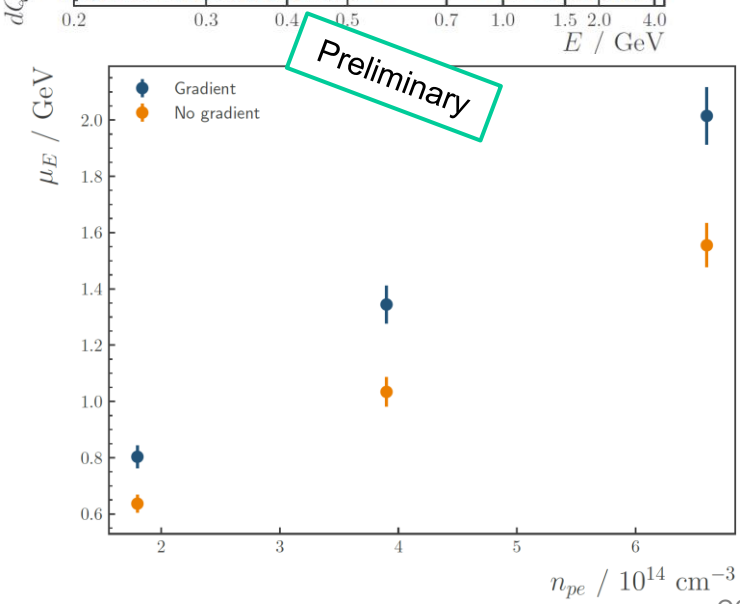
2nd AWAKE-goal : e⁻-acceleration

2017-18

2nd goal: accelerate e⁻s in self-modulated p⁺-bunch

- **First acceleration of e⁻s with p⁺-driven PWFA: up to 2GeV!!** (injected ~19MeV)
- Narrow energy-distribution & quite stable
- Work on capture efficiency
- Accelerating field ~100MeV/m-GeV/m
- Start sampling wakefields





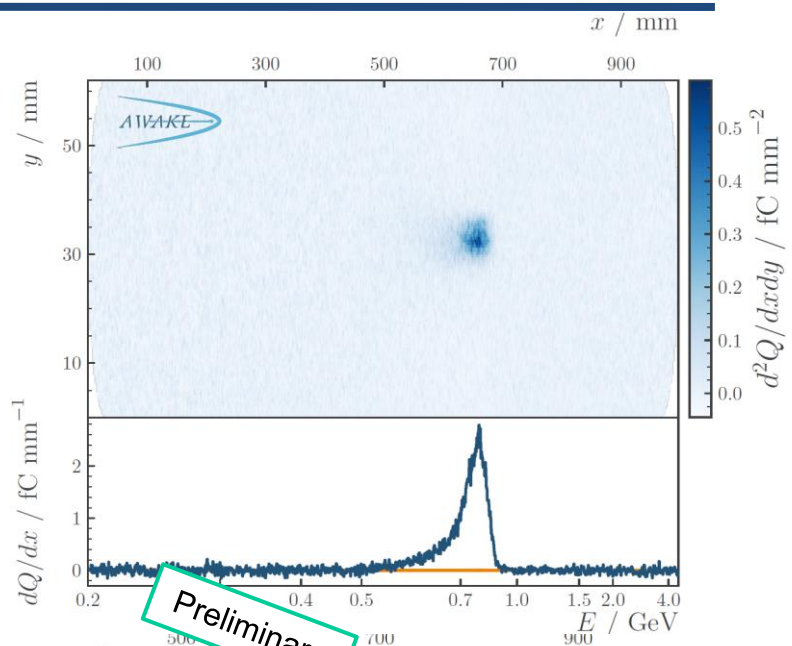
MAX-PLANCK-GESELLSCHAFT

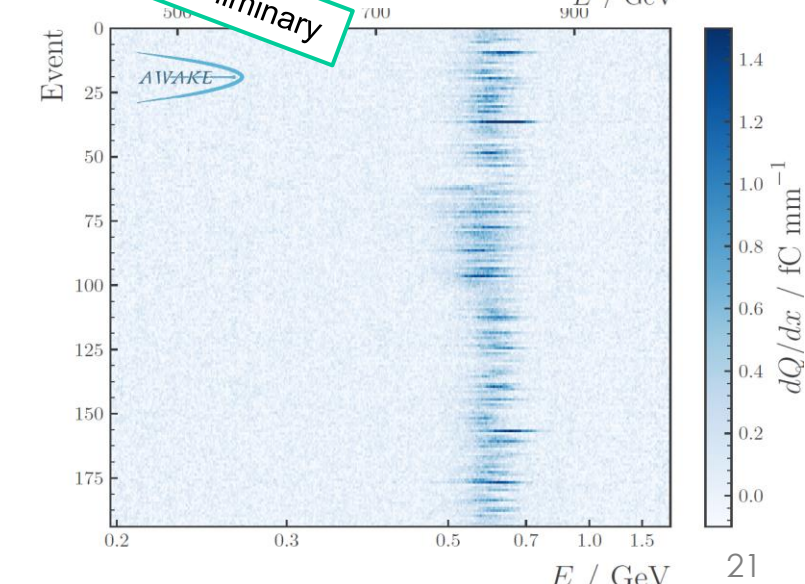
2nd AWAKE-goal : e⁻-acceleration

2017-18

2nd goal: accelerate e⁻s in self-modulated p⁺-bunch

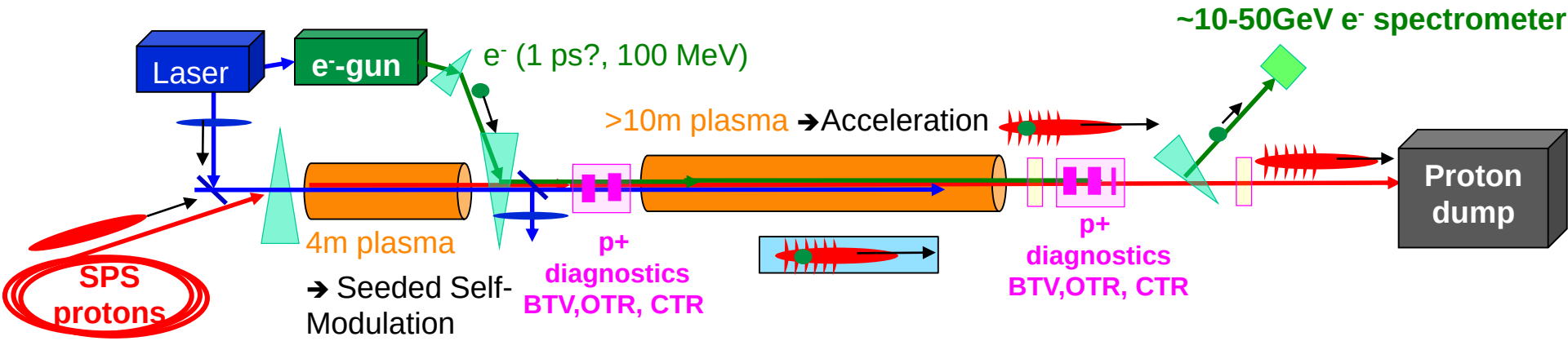
- **First acceleration of e⁻s with p⁺-driven PWFA: up to 2GeV!!** (injected ~19MeV)
- Narrow energy-distribution & quite stable
- Work on capture efficiency
- Accelerating field ~100MeV/m-GeV/m
- Start sampling wakefields





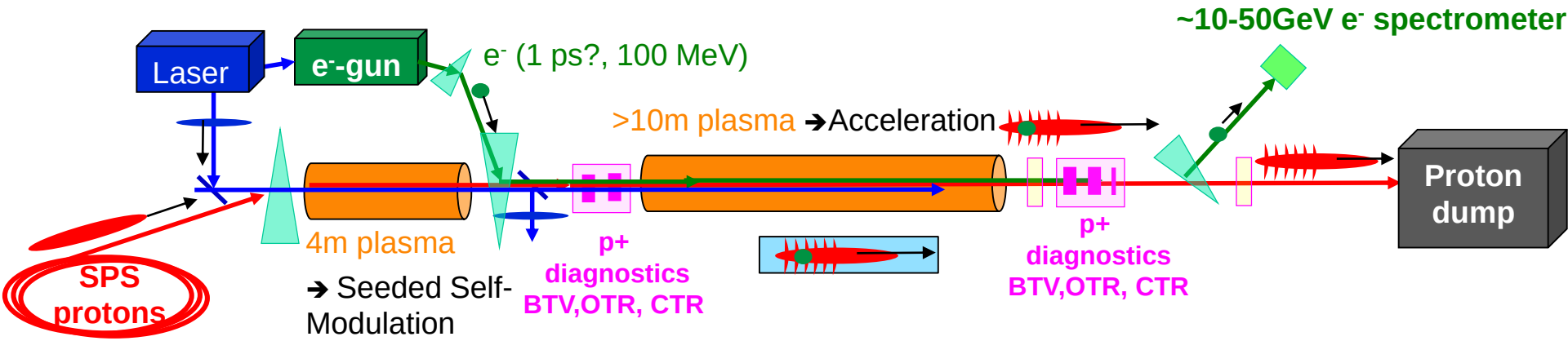
MAX-PLANCK-GESELLSCHAFT

AWAKE Run II



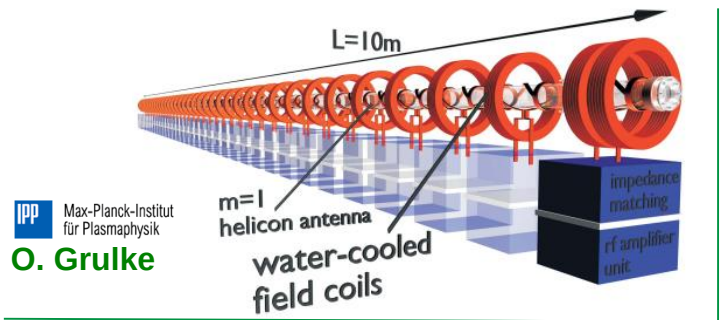
- **Split SSM-stage + ~10m acceleration stage**

AWAKE Run II



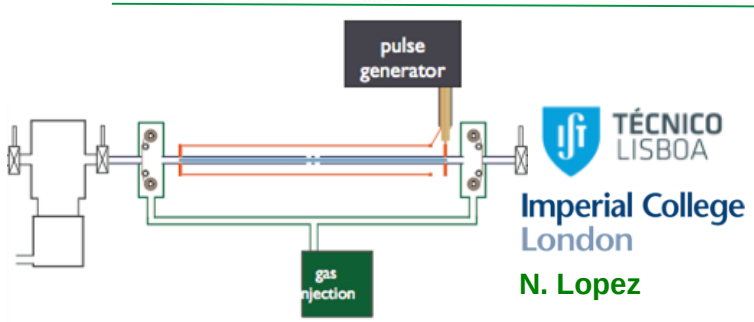
- **Split SSM-stage + ~10m acceleration stage**

Helicon-plasma (scalable to 100s of meter)



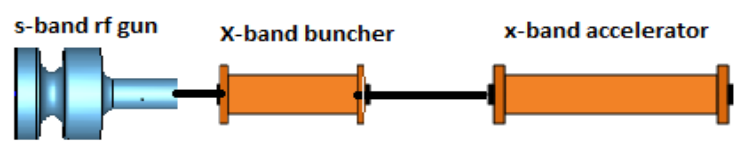
O. Grulke

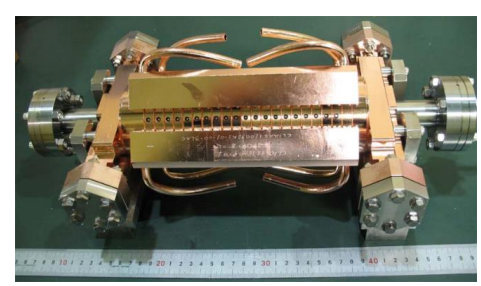
Discharge source 10m



N. Lopez

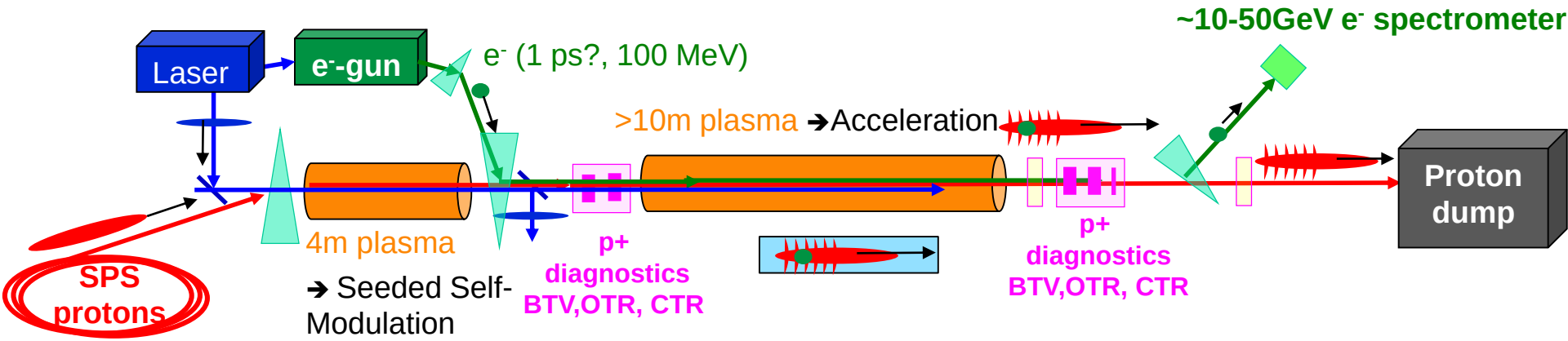
New electron source: high-energy bunch, short (under investigation)



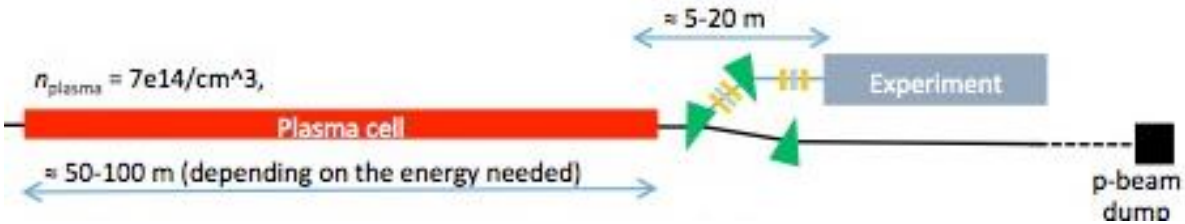


S. Döbert, CERN

AWAKE Run II



- 1st goal: Accelerate e-bunch with good beam quality (emittance, E-spread, trapping) and ~GeV/m field
- 2nd goal: Show scalability to long distances
- After: Physics applications → fixed target



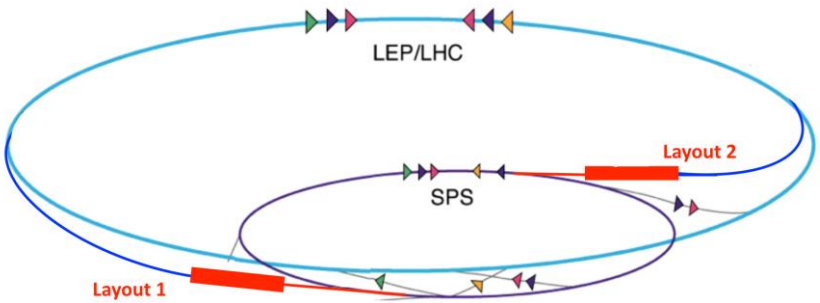
MAX-PLANCK-GESELLSCHAFT

AWAKE

Application: e^--p^+ collider @ LHC ?

Option 1: AWAKE Run II/III vs. LHC-p^+

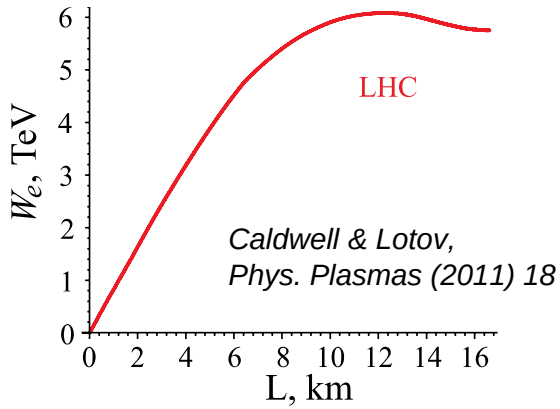
- Create ~50 GeV e^--beam within 50−100 m of plasma driven by SPS protons → large cross-sections/low luminosity
- Already E_e = 10 GeV, E_p = 7 TeV, $\sqrt{s}$ = 530 GeV exceeds HERA cm energy



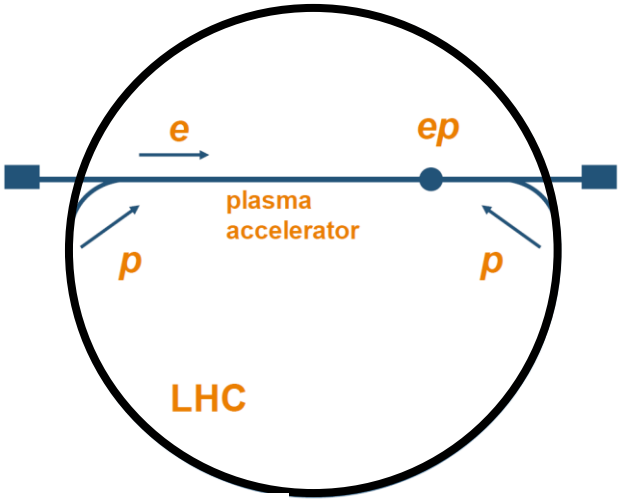
G. Xia et al., Nucl. Instrum. Meth. A (2014) 740

Option 2: LHC-driven accelerator

- E_e = 3 TeV vs. E_P = 7 TeV yields $\sqrt{s}$ = 9 TeV (~30 higher than HERA)



Caldwell & Lotov, Phys. Plasmas (2011) 18



Caldwell & Wing, Eur. Phys. J. C (2016) 76

MAX-PLANCK-GESELLSCHAFT

AWAKE

Summary

- **AWAKE = first p^+-driven plasma wakefield accelerator → prospect of HEP without staging**
- **1st goal:**
  Demonstration of seeded self-modulation of a long p^+-bunch
  - **Defocused protons + microbunches + modulation-frequency (very reproducible)**
- **2nd goal:**
  Acceleration of e^--bunch for first time with p^+-driven PWFA

Future:

- **Run II: SSM-stage + acceleration stage → ~10GeV**
- **Possible applications: e.g. e^--p^+ collider with LHC**

MAX-PLANCK-GESELLSCHAFT

AWAKE

Thanks for your attention!

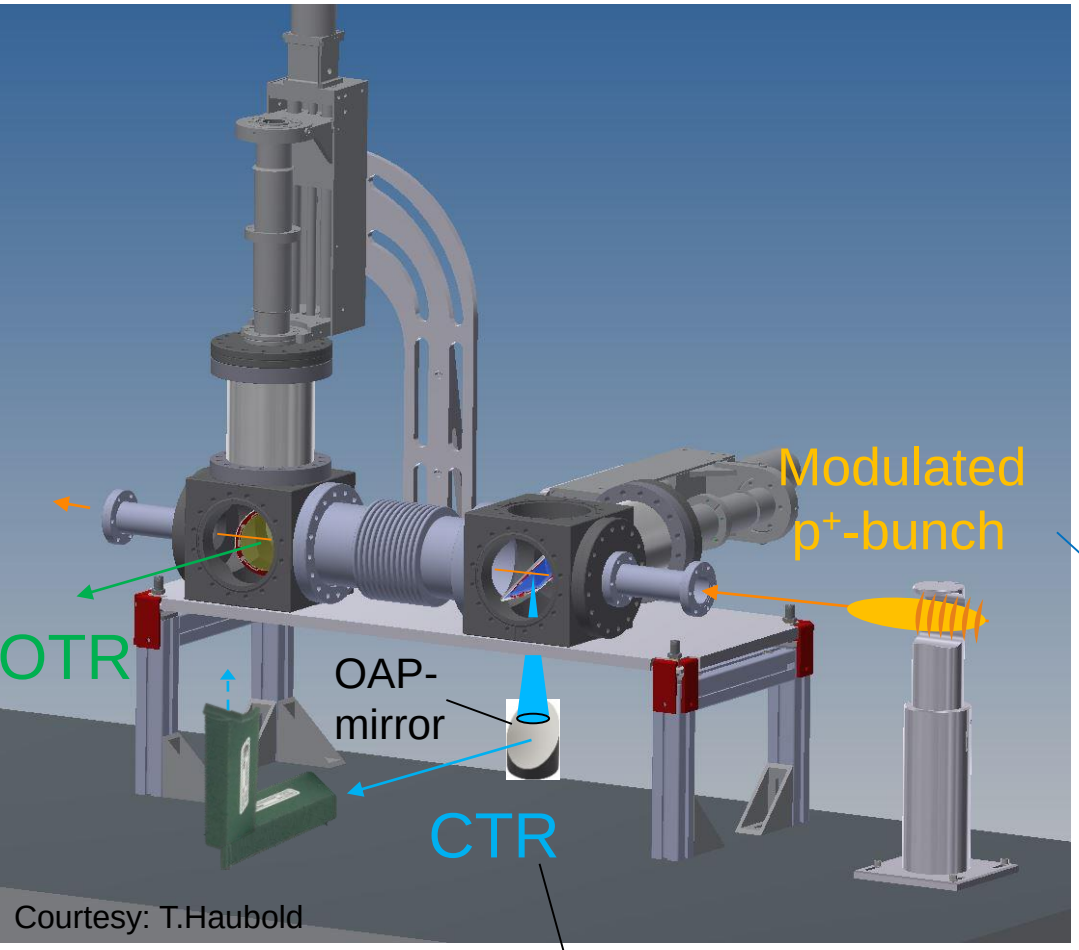
MAX-PLANCK-GESELLSCHAFT

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

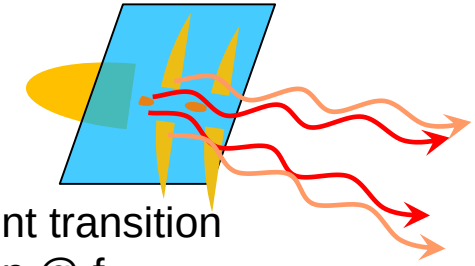
AWAKE

Additional slides

SSM-Diagnostics via CTR



Courtesy: T.Haubold



Coherent transition radiation @ $f_{modulation}$ (90-280GHz)

Signal:

f_{CTR} ~260GHz

Reference:

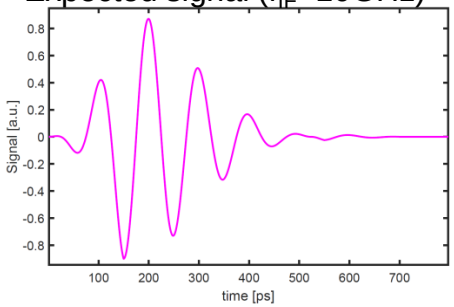
f_{ref}~270GHz

Mixer

Intermediate frequency:

f_{IF} ~5-20GHz

Expected signal (f_{IF}=10GHz)

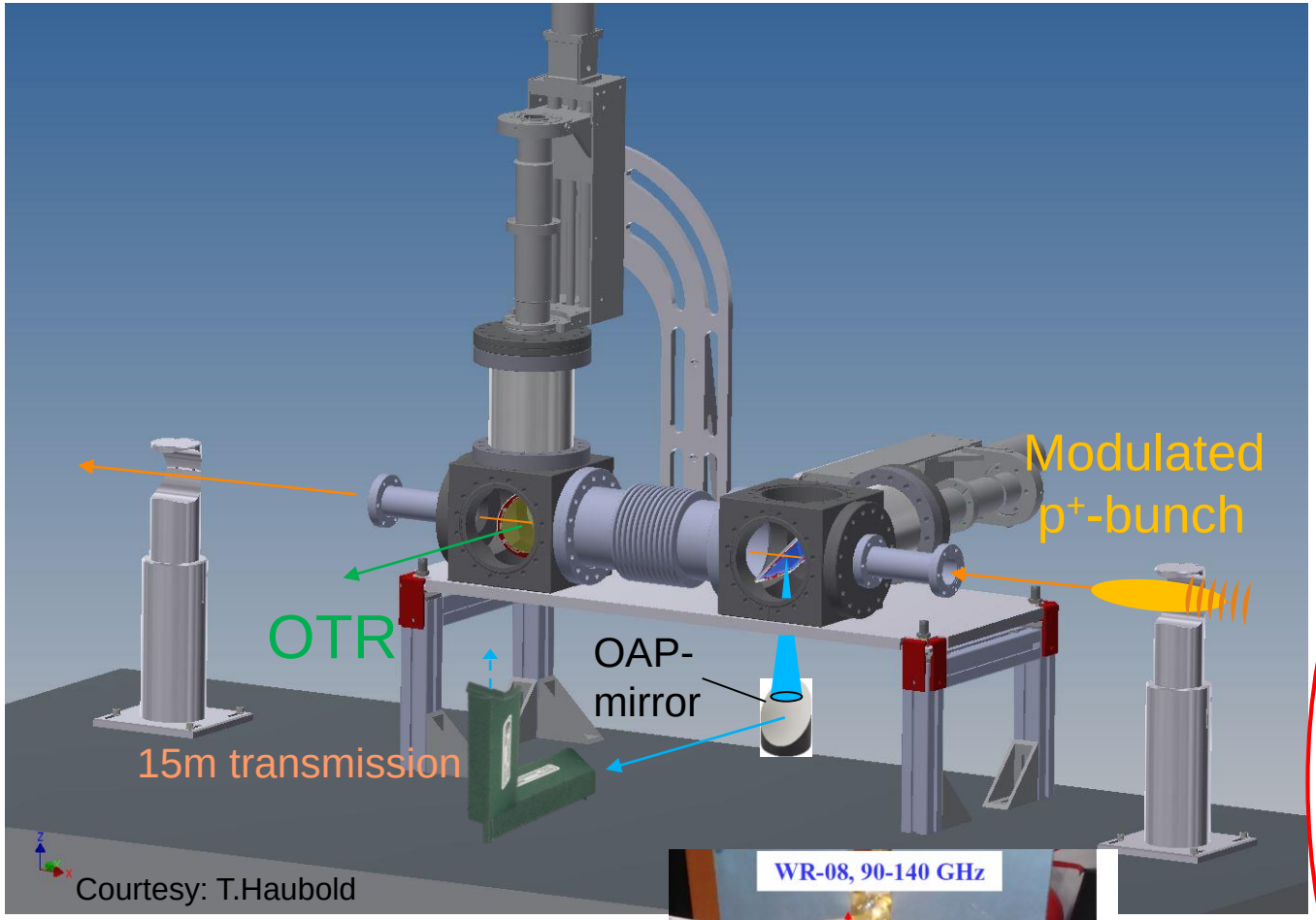


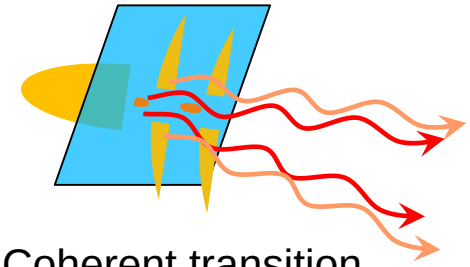
Coupled into WR90 waveguide →15m transmission

MAX-PLANCK-GESELLSCHAFT

AWAKE

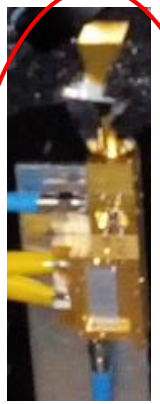
SSM-Diagnostics via CTR

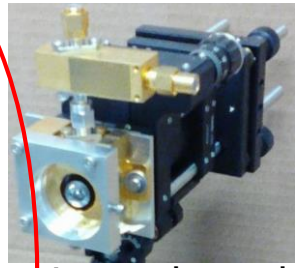




Coherent transition radiation @ $f_{modulation}$ (90-280GHz)

Frequency:
Heterodyne mixing





Laser-based

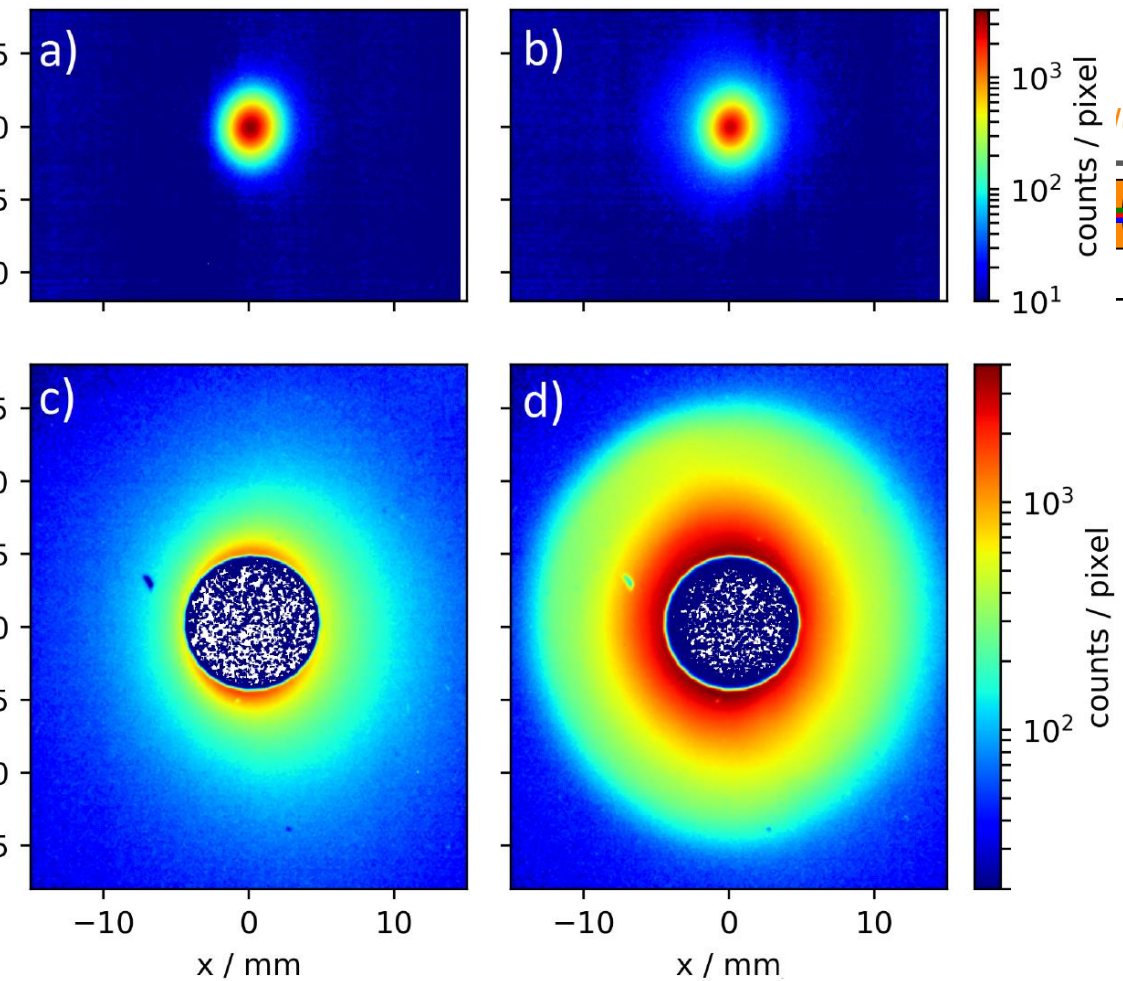
Waveguide-based

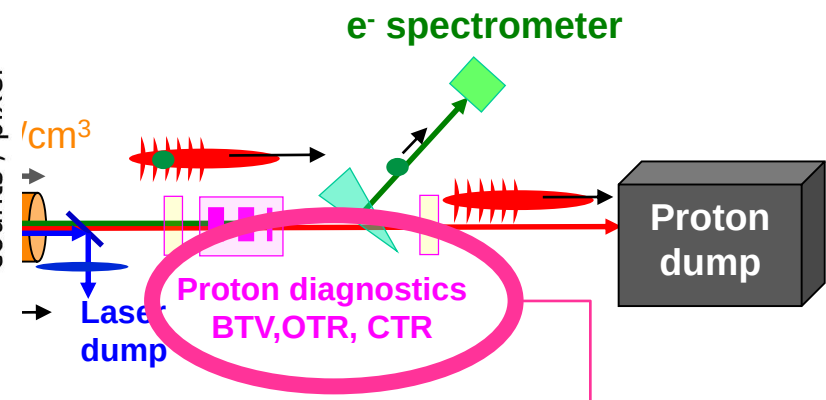
Amplitude:
Schottky diodes

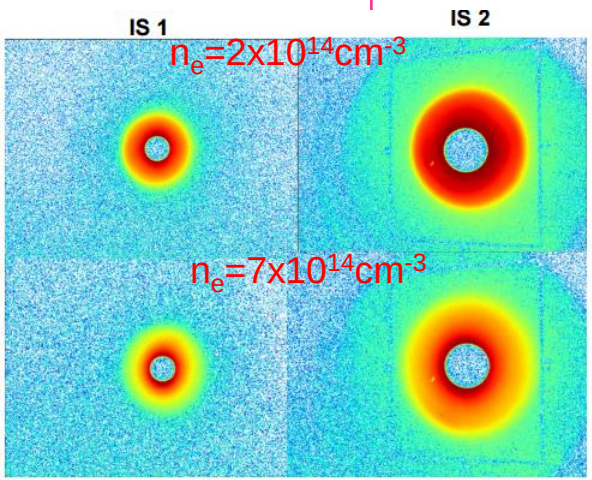
MAX-PLANCK-GESELLSCHAFT

AWAKE

1st goal of AWAKE: SSM







MAX-PLANCK-GESELLSCHAFT

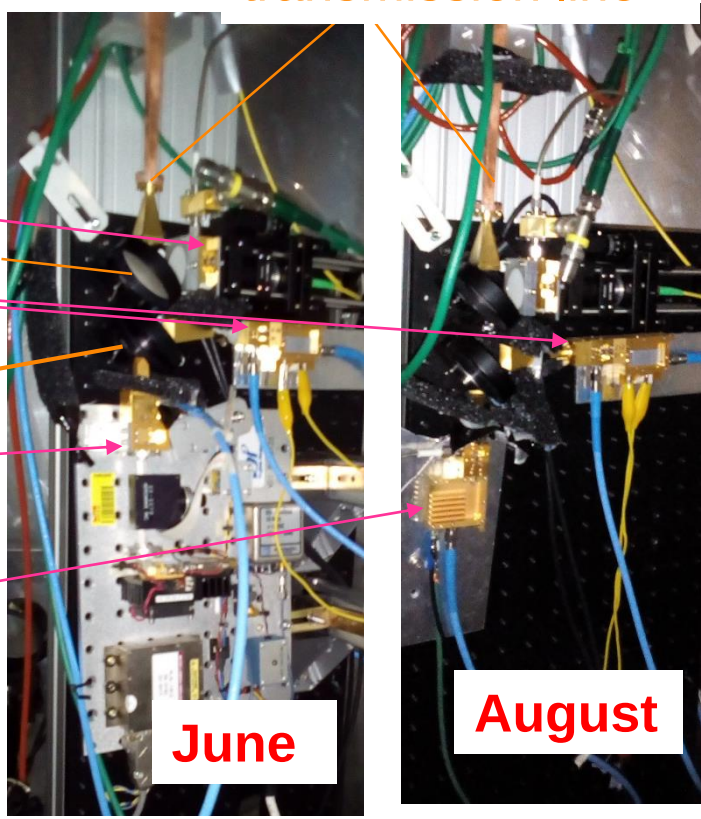
AWAKE

Diagnostic setup

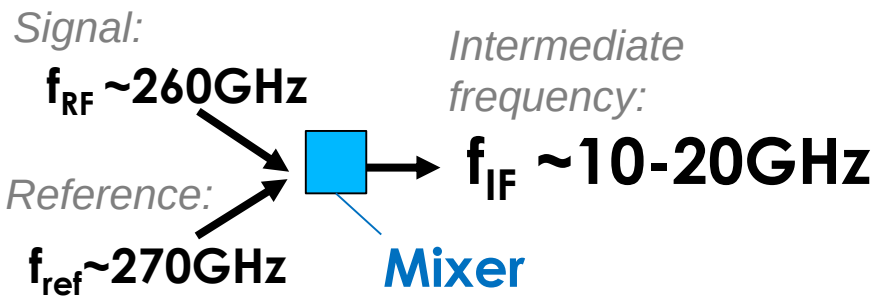
- **3 Heterodyne receivers for CTR:**
  - **Laser-based mixing** **(last presentation)**
  - **WR8 / 90-140GHz: Radiometer-system**[new]
  - **WR3.4 / 255-270GHz: VDI-system from EPFL**

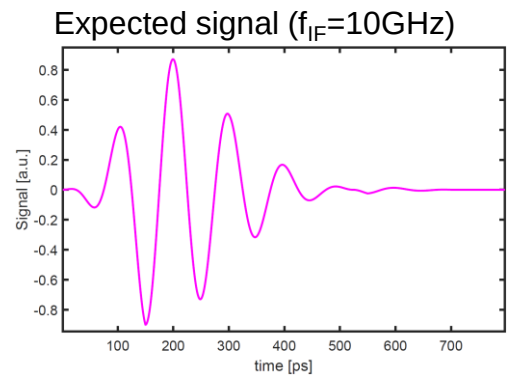
  ↳ **replaced by WR4.3/170-260GHz system**

- **Can detect 2nd harmonics of $f_{modulation}$**



Measurement principle





- f_{ref} from frequency-multiplication of tunable local oscillator
  $f_{ref} = n_{harm} f_{LO}$

➔ Also mixing with weaker parasitic reference frequencies
  $f_{ref} = n_{harm,1} f_{LO}$. ($n_{harm,1} = n_{harm}$ +/-1 , …)

➔ Confirm that signal on oscilloscope is from mixing with correct reference frequency:

- $f_{IF} = | f_{RF} - n_{harm} f_{LO} |$ ➔ $n_{harm} = \Delta f_{IF} / \Delta f_{LO}$

fix

measured

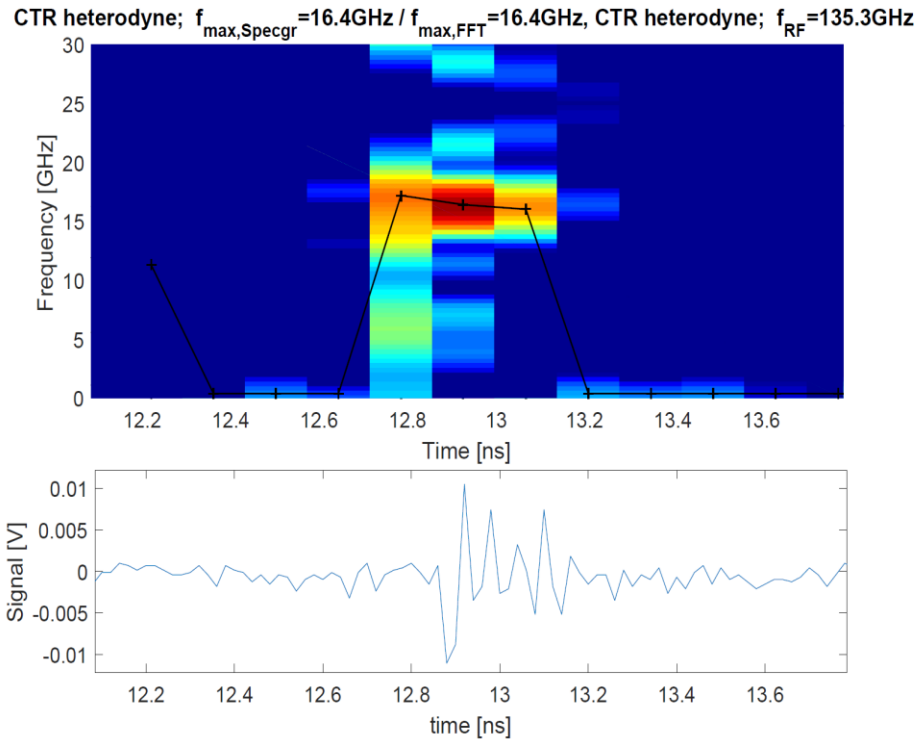
setting

to be determined

33

CTR-signal from mixer

- **Short signal, close to expected length**
- **Very precise**
- **Strong single-frequency-component (find via spectrogram)**
  → f_{IF}



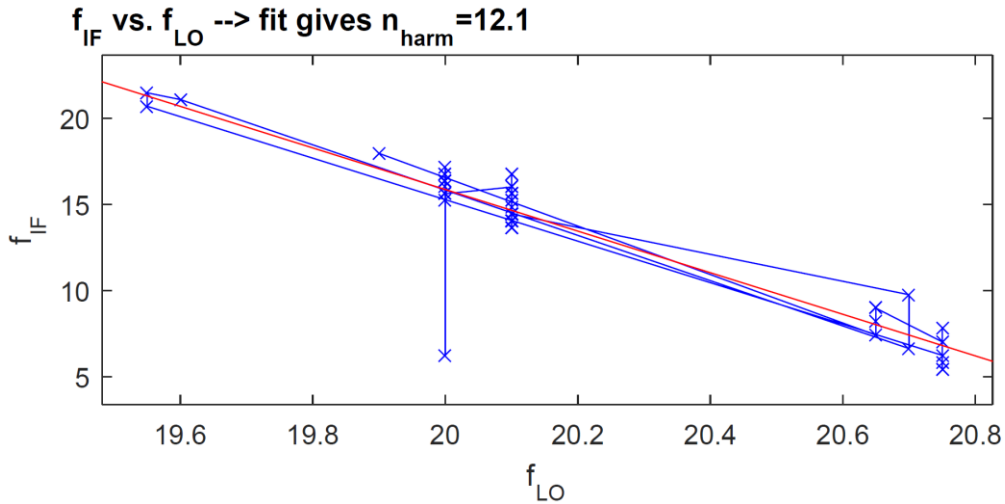
CTR-analysis

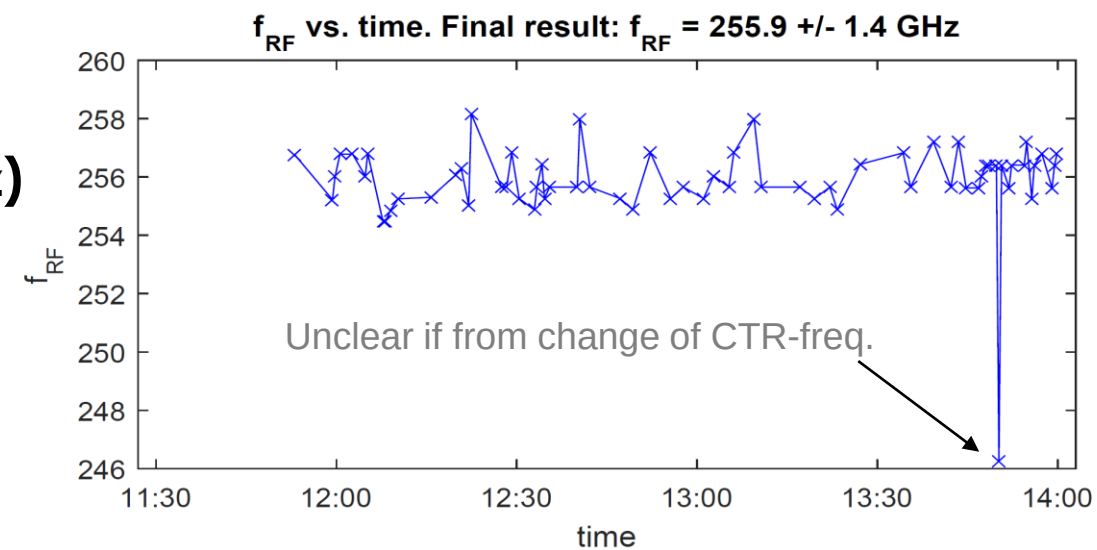
Fit f_{IF} vs. f_{LO} to check n_{harm}

→ In general, expected n_{harm} =8 / 12 / 24 is confirmed (sometimes ambiguous)

→ $f_{RF} = n_{harm} f_{LO} +/- f_{IF}$

→ Average & standard deviation of f_{RF} (here: 255.9GHz +/- 1.4GHz)





MAX-PLANCK-GESELLSCHAFT

Results of CTR-analysis

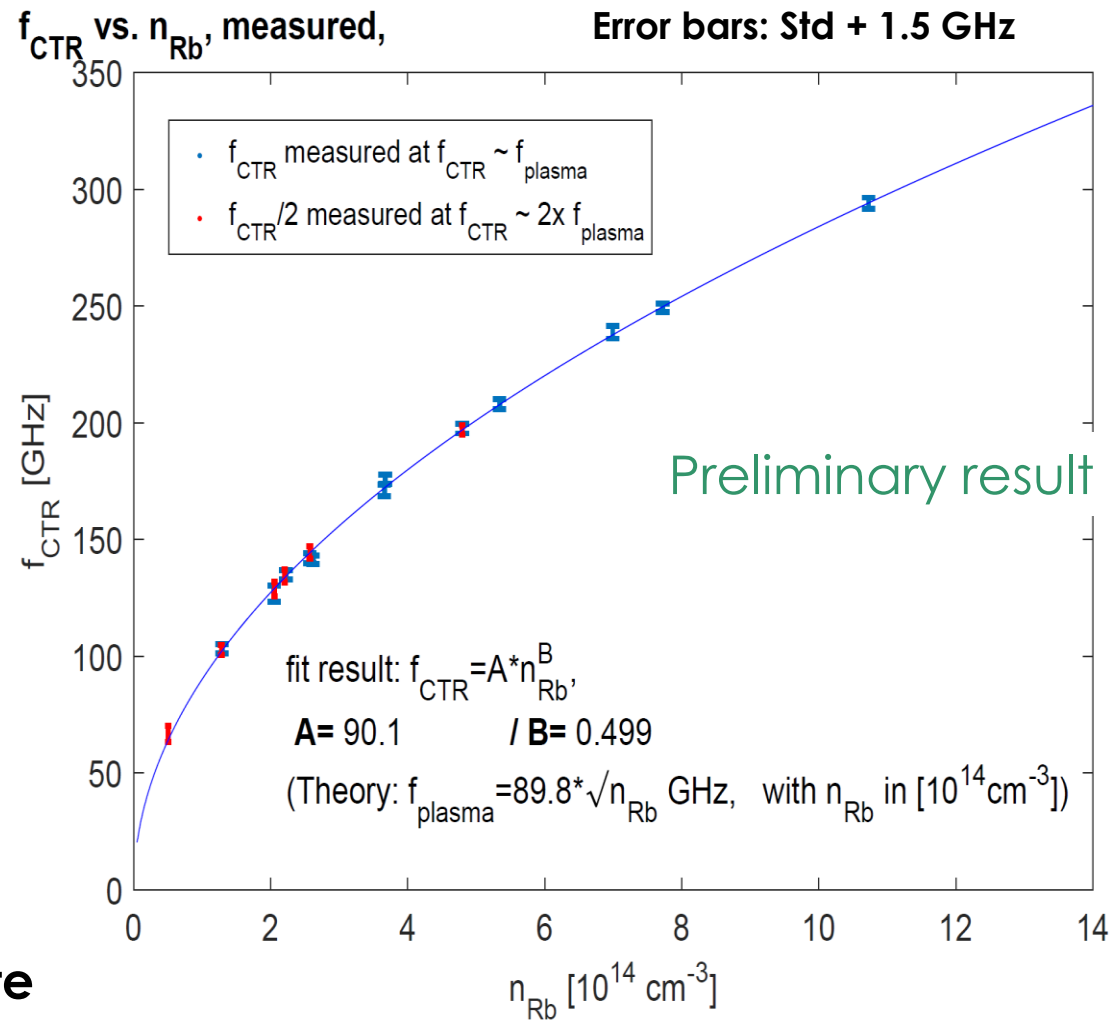
Result: f_{CTR} vs. n_{RB} ← vapour

$f_{CTR} = f_{plasma}(n_{Rb})$

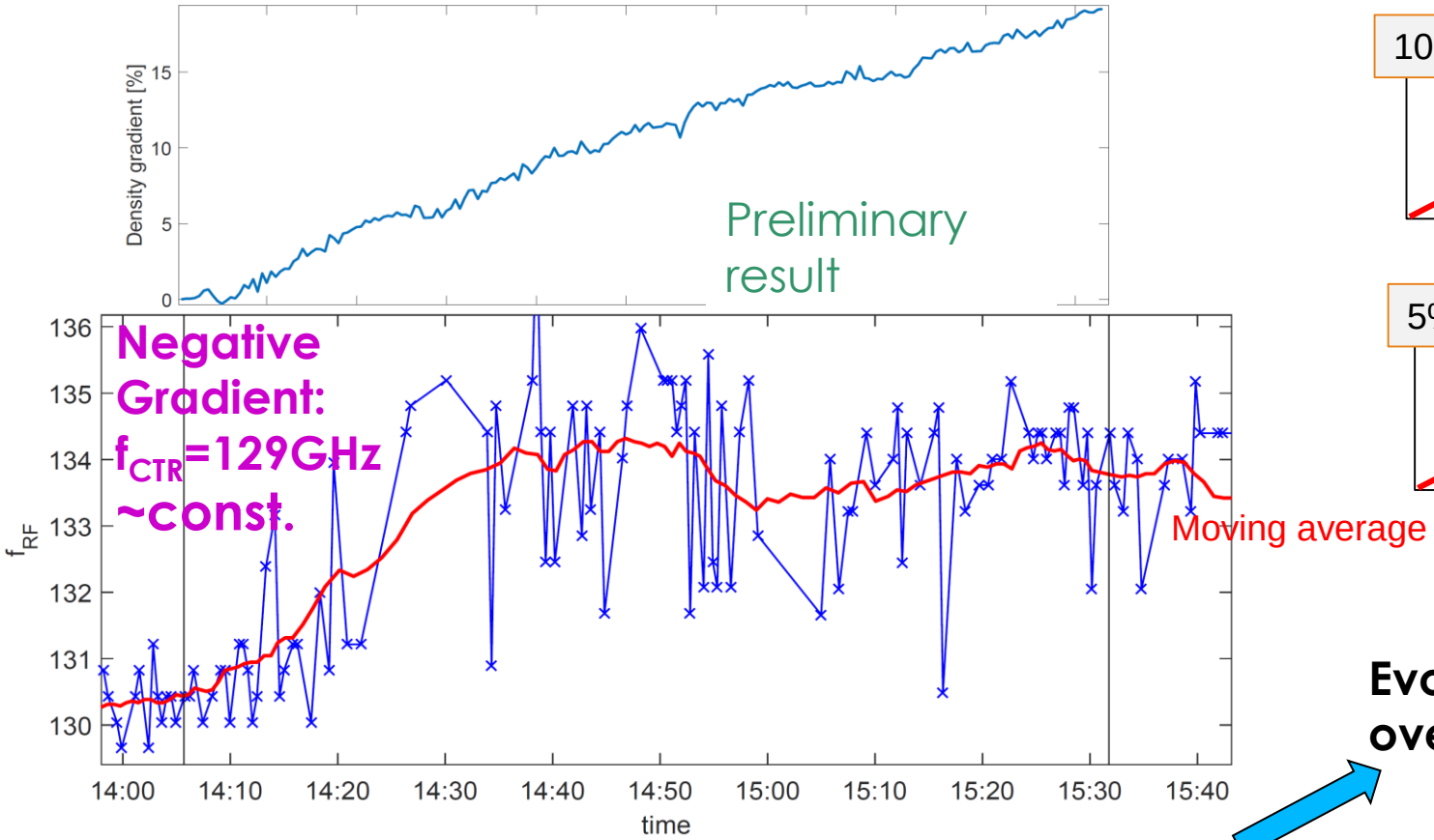
- ➔ SSM with $f_{CTR}=f_{plasma}$ as predicted
- ➔ Rb fully ionized
- Good match between fundamental & 2nd harmonics

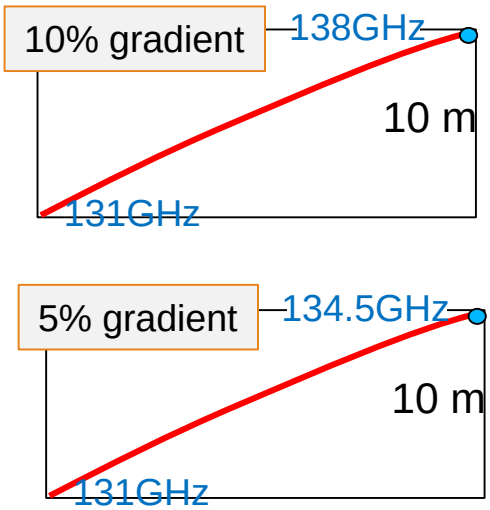
→ proof that correct $n_{harm}(f_{LO})$ was chosen

- Excellent fit result: parameters within 0.3%
- Error analysis incomplete



f_{CTR}-dependence on n_{Rb}-gradient





Evolving interaction over several meters!

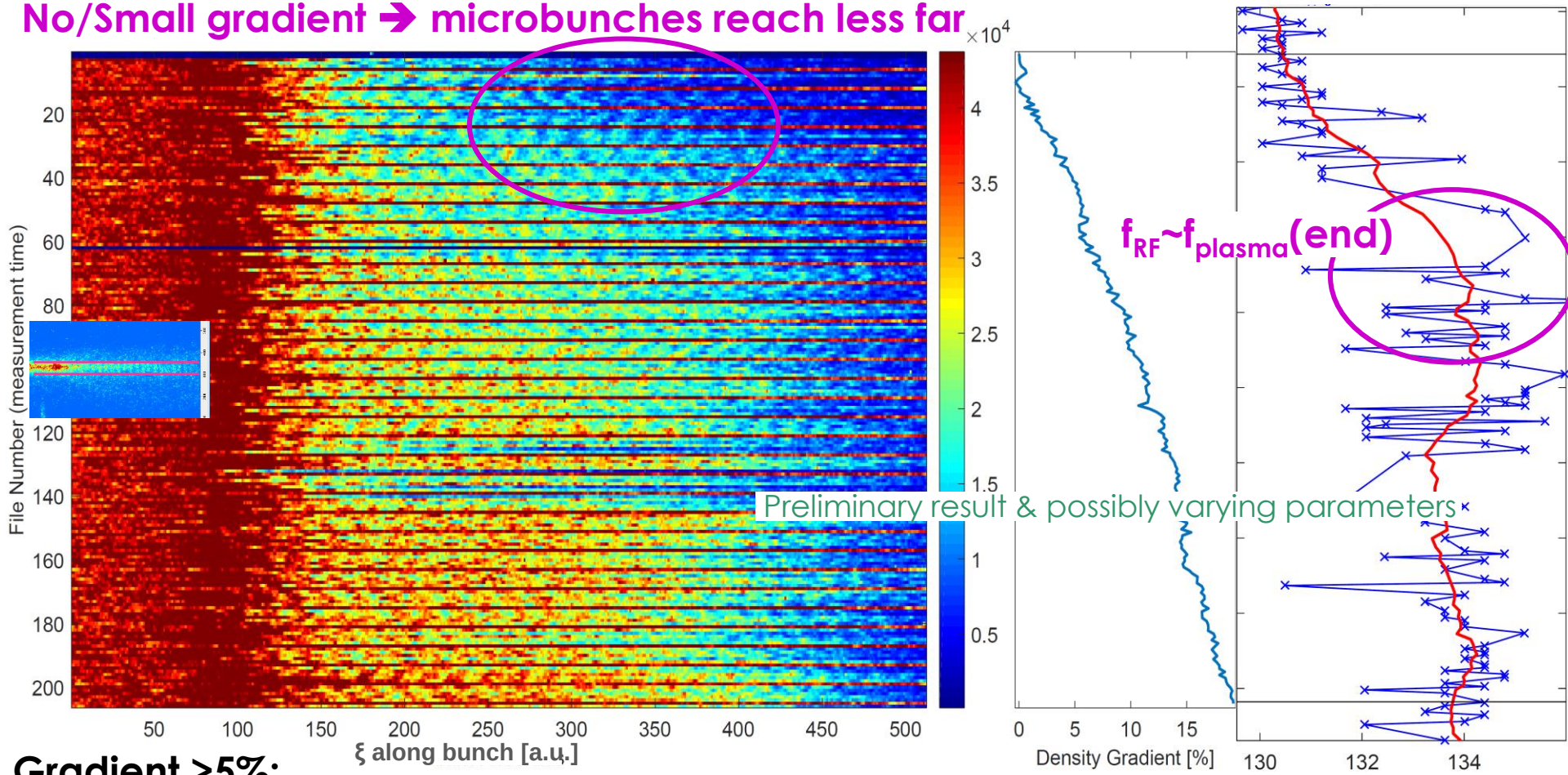
- **Frequency increasing with positive gradient, but basically constant with negative gradient**
  → Explanation from SSM?

MAX-PLANCK-GESELLSCHAFT

AWAKE

SSM-Dependence on n_{Rb}-gradient

No/Small gradient ➔ microbunches reach less far



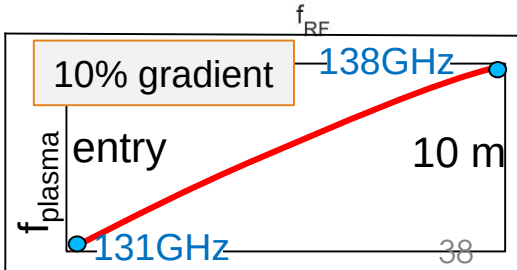
Gradient >5%:

- **Microbunches longer visible after seeding**
- **f_{RF} corresponds more to f_{plasma}(end)**

➔ longer interaction in plasma?

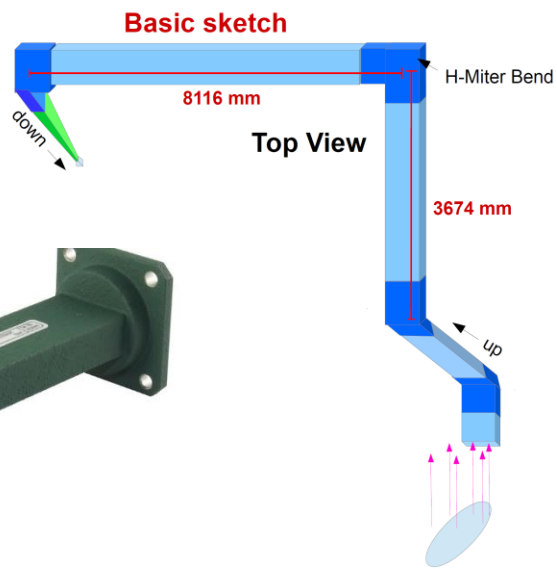
Negative Gradient: f_{CTR}=129GHz≈const.

Check with simulations ?!

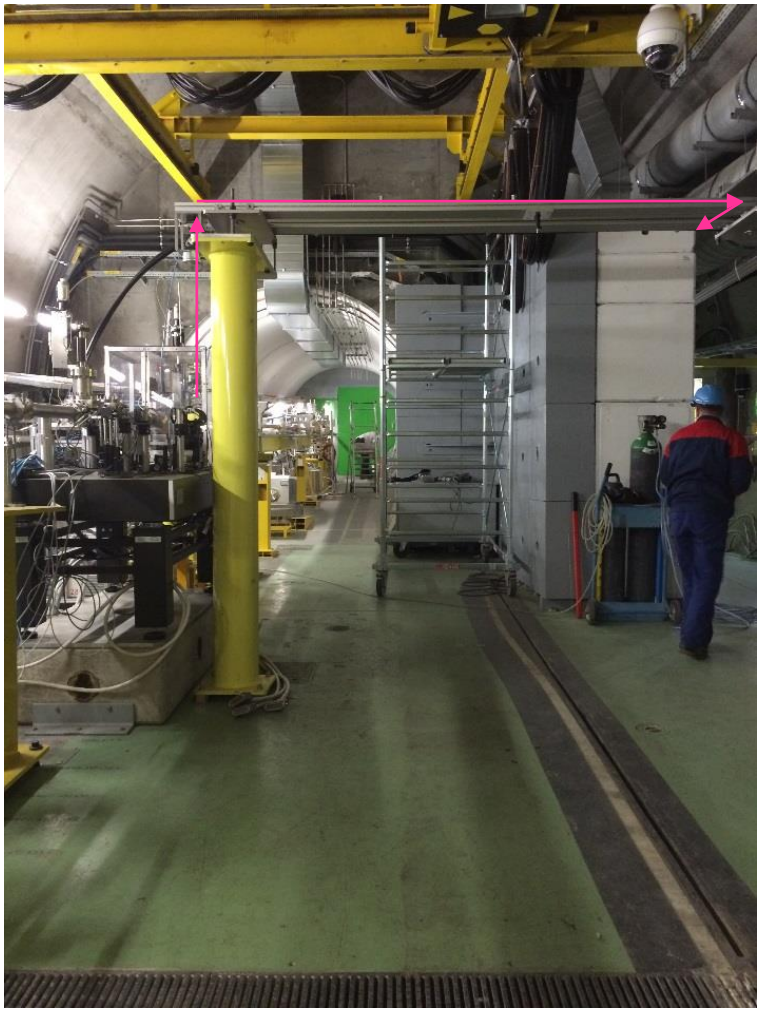


Waveguide Transmission Line

- **Detector behind shielding wall**
- **15m of overmoded waveguide WR90 (fundamental mode 8-12GHz)**



E-field polarization



MAX-PLANCK-GESELLSCHAFT

AWAKE