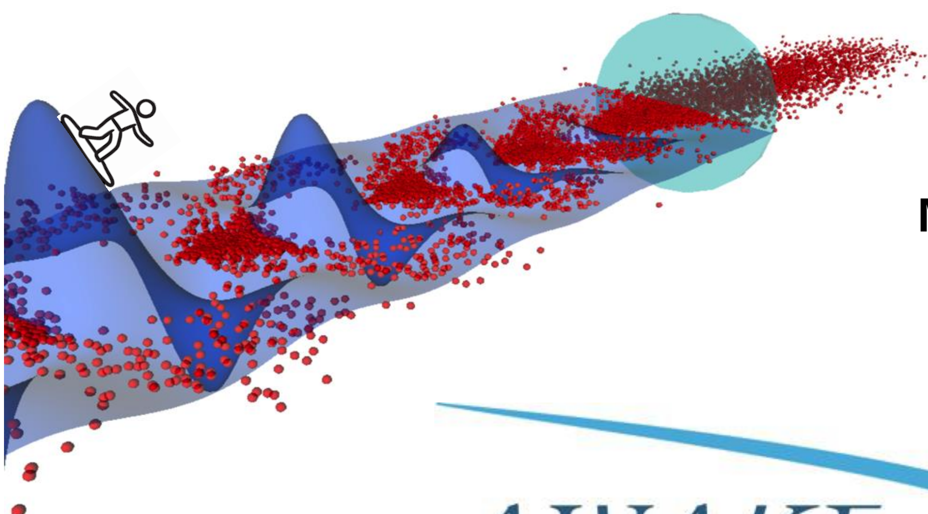
First results of the advanced acceleration experiment AWAKE



Falk Braunmüller on behalf of the AWAKE collaboration

19 December 2018

MPP yearly review meeting

MPP, Munich

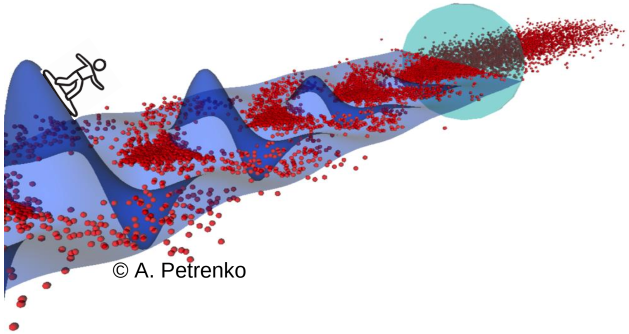
AWAKE

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 & outlook**



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Present and future colliders

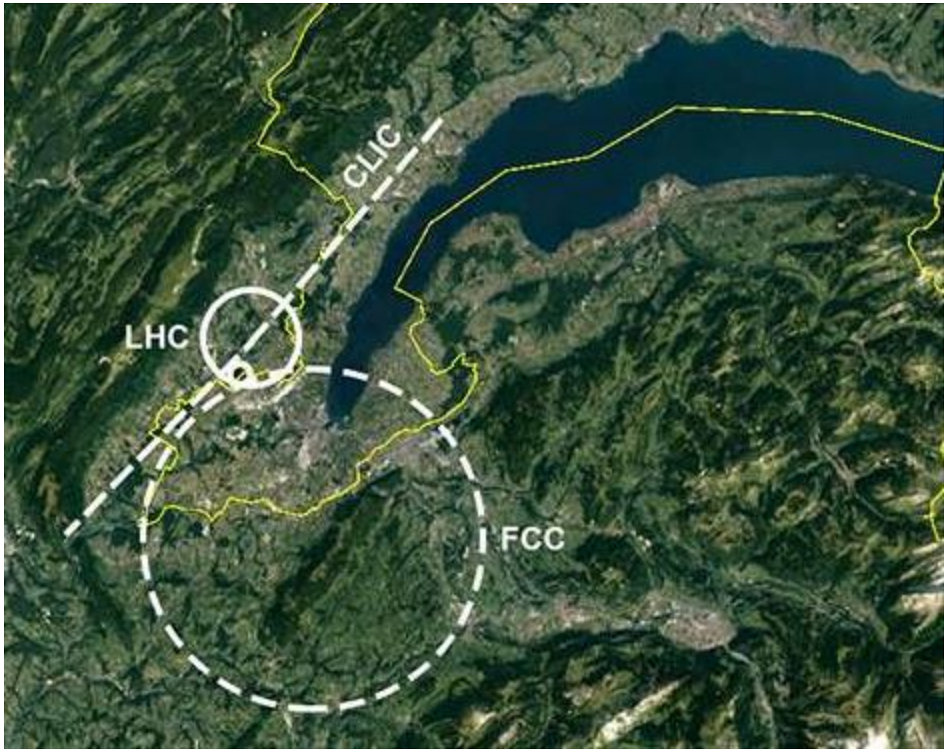
Possible future RF-driven accelerators:

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

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)

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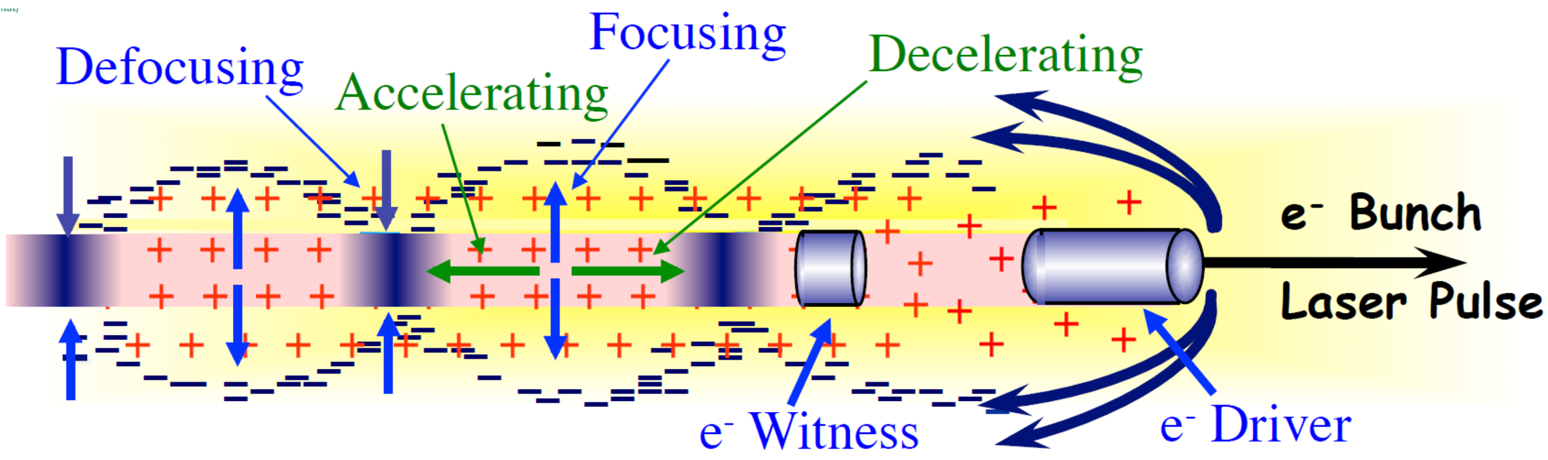
Plasma acceleration



- Overcomes break-down limitation of RF-accelerators
- **Laser / e⁻ driver**: pushes out plasma e⁻'s

→ oscillate in & out: 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**?**

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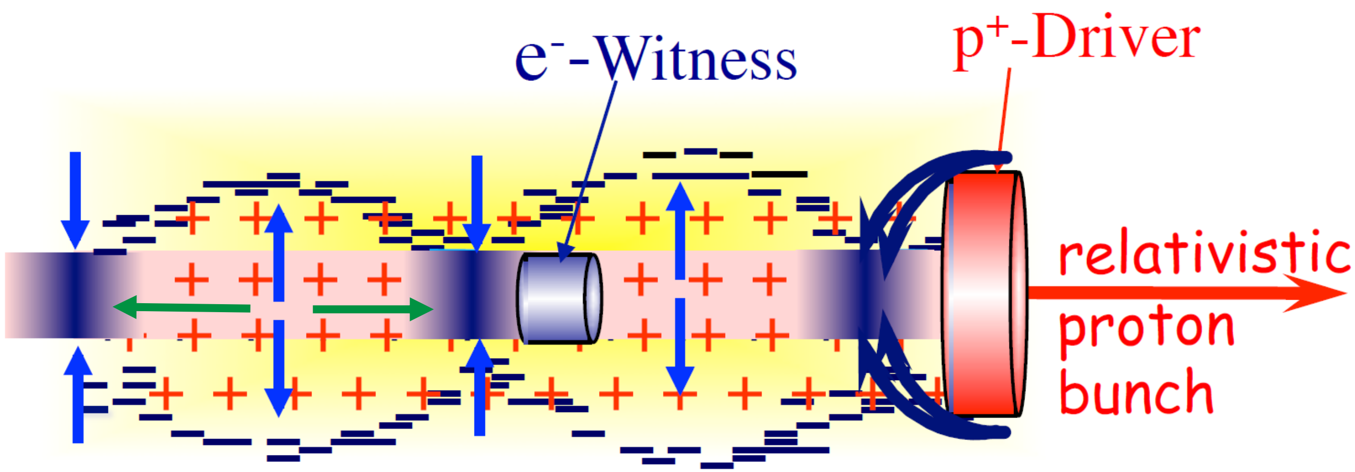
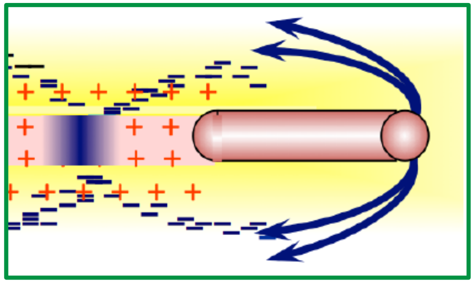
p+-driven PWFA





→ same with different phase

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

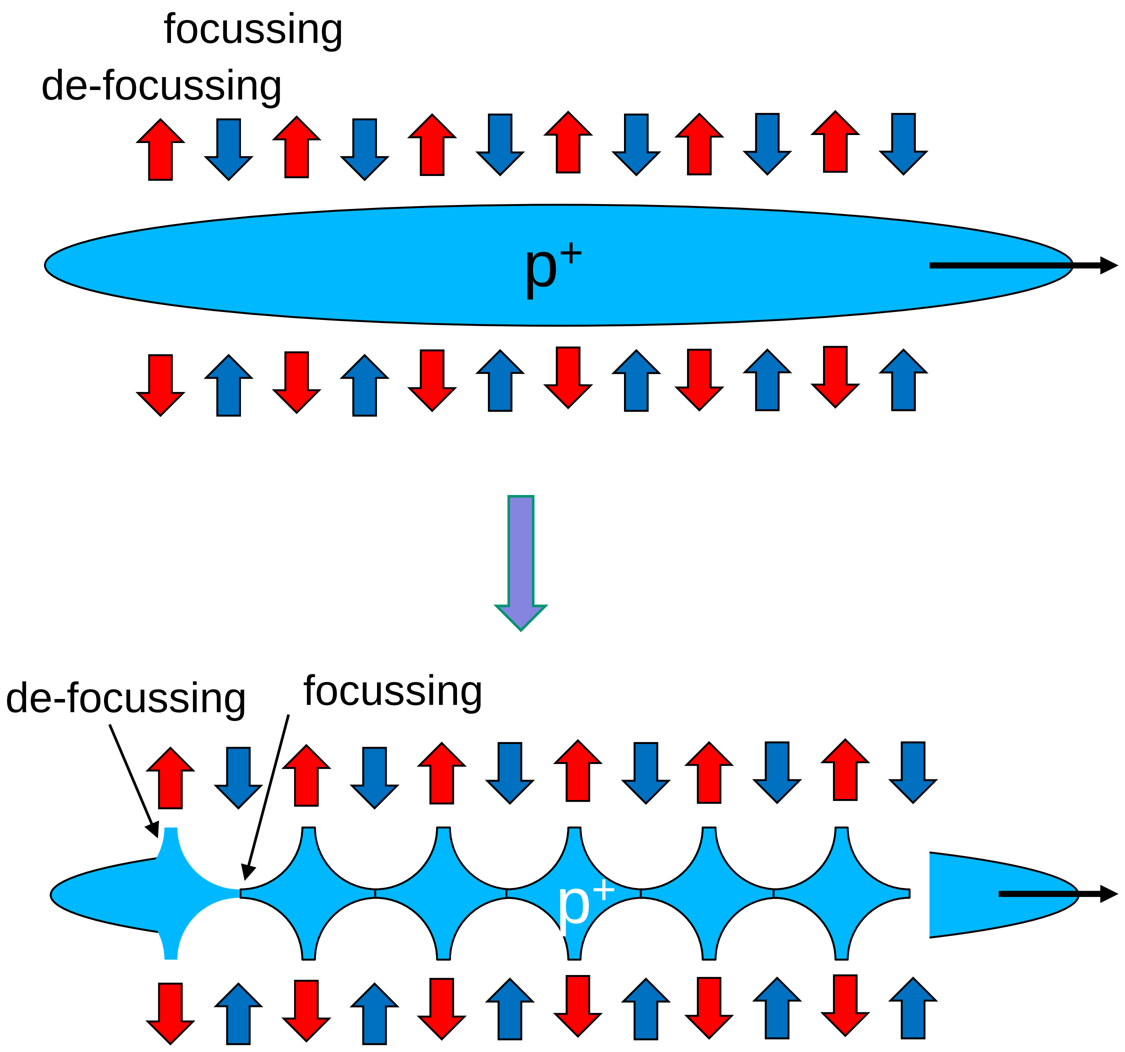
- **Solution: proton self-modulation**

Self-Modulation Instability (SMI)

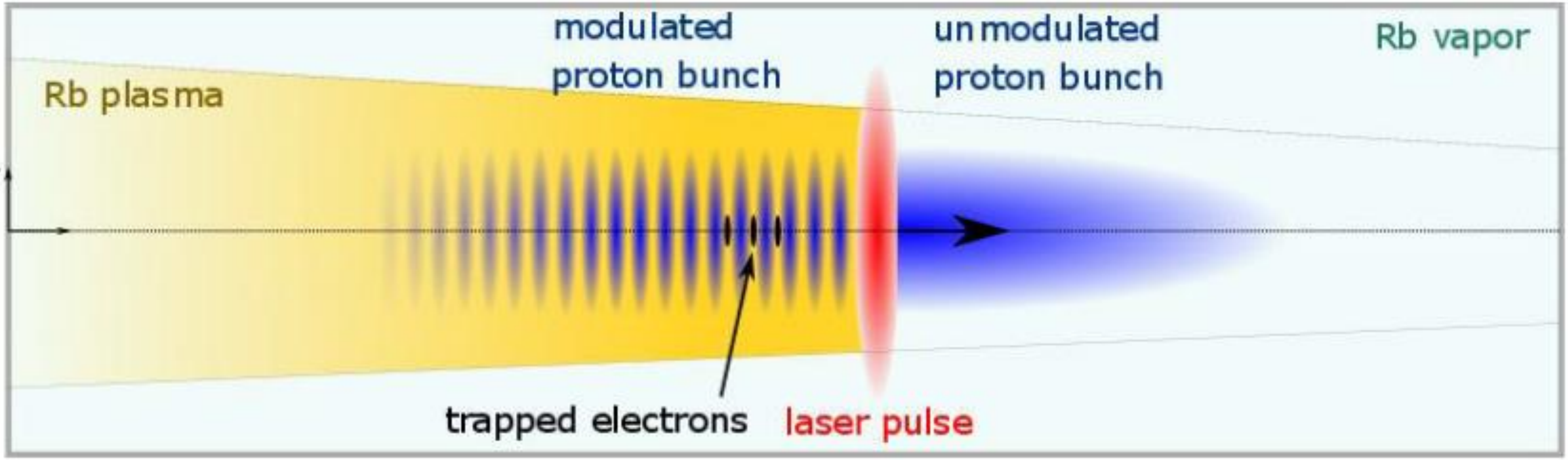
CERN SPS p^+ bunch 10cm **long**
→Not efficient for driving wakefields for the plasma densities of AWAKE
($\lambda_{pe} \approx 2\ mm$)

BUT: **Transverse Modulation of p^+ bunch** with periodicity λ_{pe} through transverse wakefields!

→"Instability" (Back-coupling)
Modulation
→Higher local bunch density
→Stronger wakefields
→Resonant growth



Seeded Self-Modulation (SSM) for AWAKE



AWAKE: Laser pulse copropagating with the p^+ bunch
→ Sharp ionation front (plasma density step) seeds the SMI
→ Phase stable modulation of the long proton bunch into micro bunches
→ Resonantly driving wakefields by the micro bunches

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SPS-bunch (400GeV, $3 \cdot 10^{11}$ p^+) carries enough energy for single-stage HEP-accelerator

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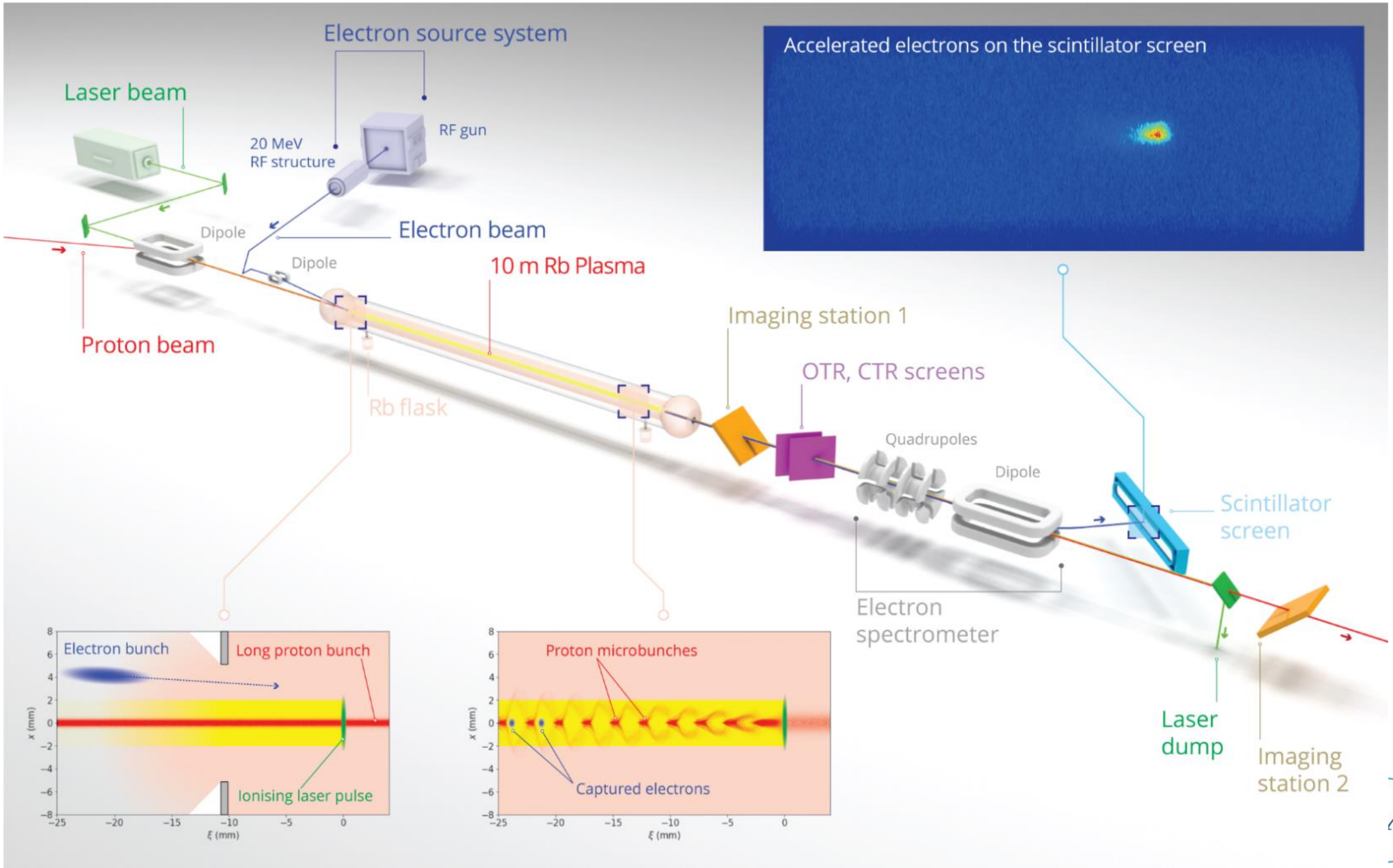
A.-M.

Experimental setup

- 10m long **rubidium (Rb) vapor source,** temperature controlled by surrounding Galden fluid
- A 4TW **laser ionizing** the Rubidium vapor and seeding the self-modulation of the drive bunch
- Driver: 400 GeV **proton bunch** from CERN's SPS accelerator
- Injection of a **witness electron bunch for acceleration**



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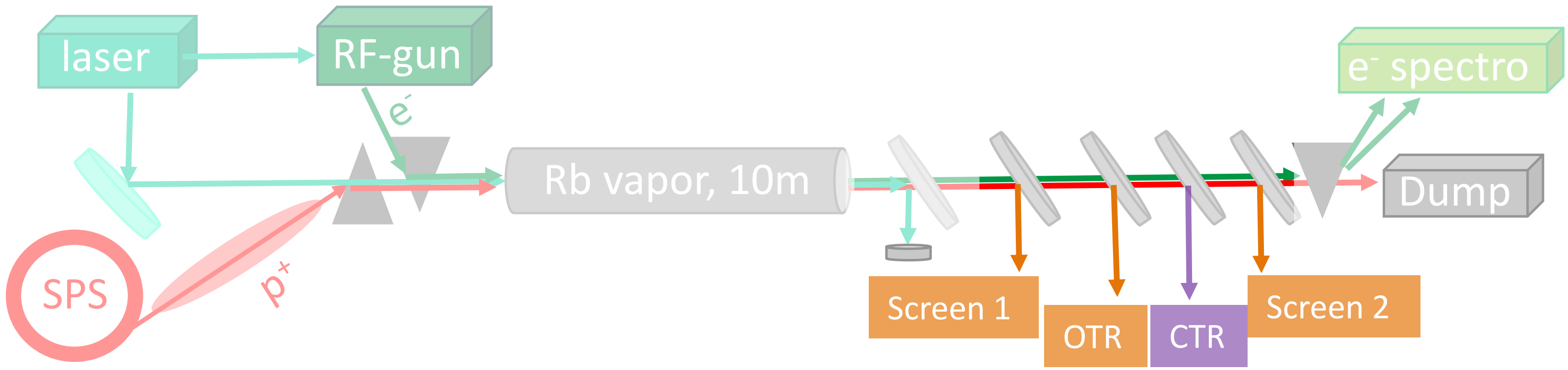
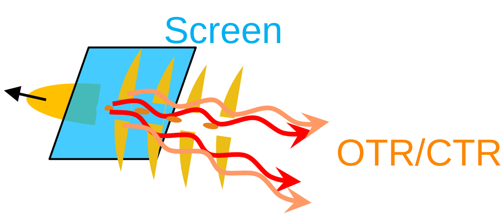
1st AWAKE-goal: SSM-study



2016-17

- **1st goal: Demonstrate Seeded Self-Modulation of a long proton bunch: $\sigma_z >> \lambda_{pe} \sim n_e^{-1/2}$**



- Diagnostics: Two screen measurement + OTR on streak camera + CTR

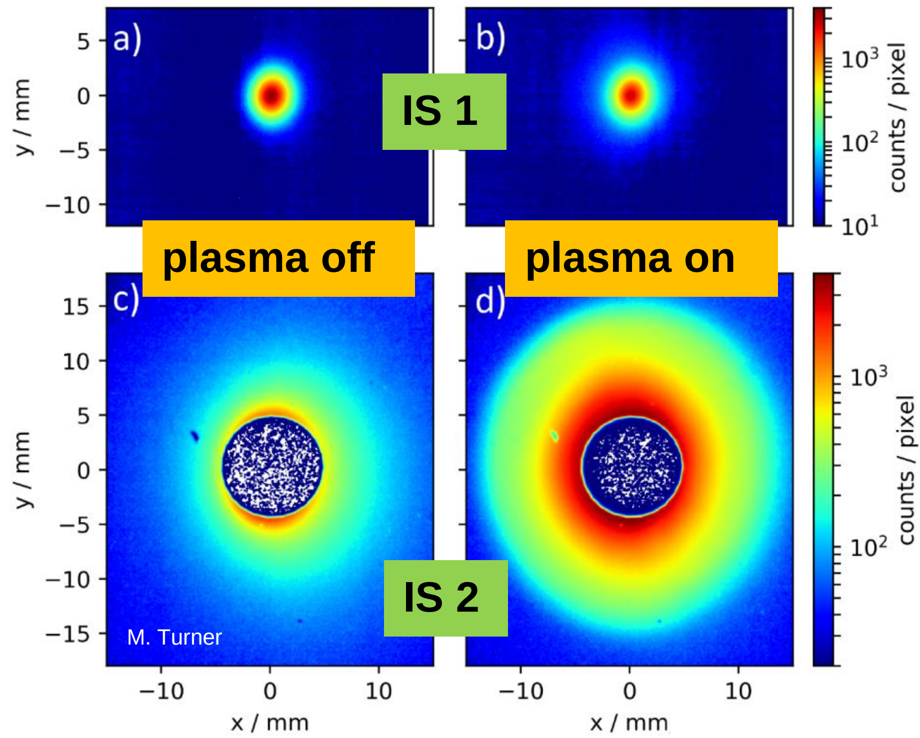
- Observables: Defocused protons + bunch-profile + modulation-frequency

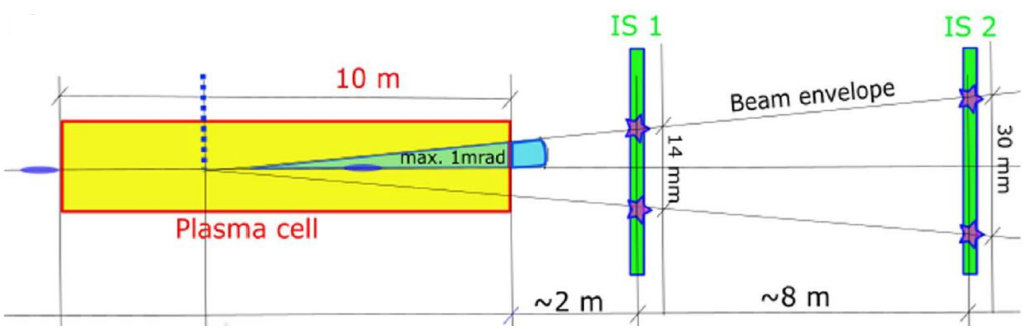
1^{st} AWAKE-goal: SSM

Two-screen BTV:

- Defocused p^+s with plasma

➔ strong defocussing fields from wakefields inside plasma

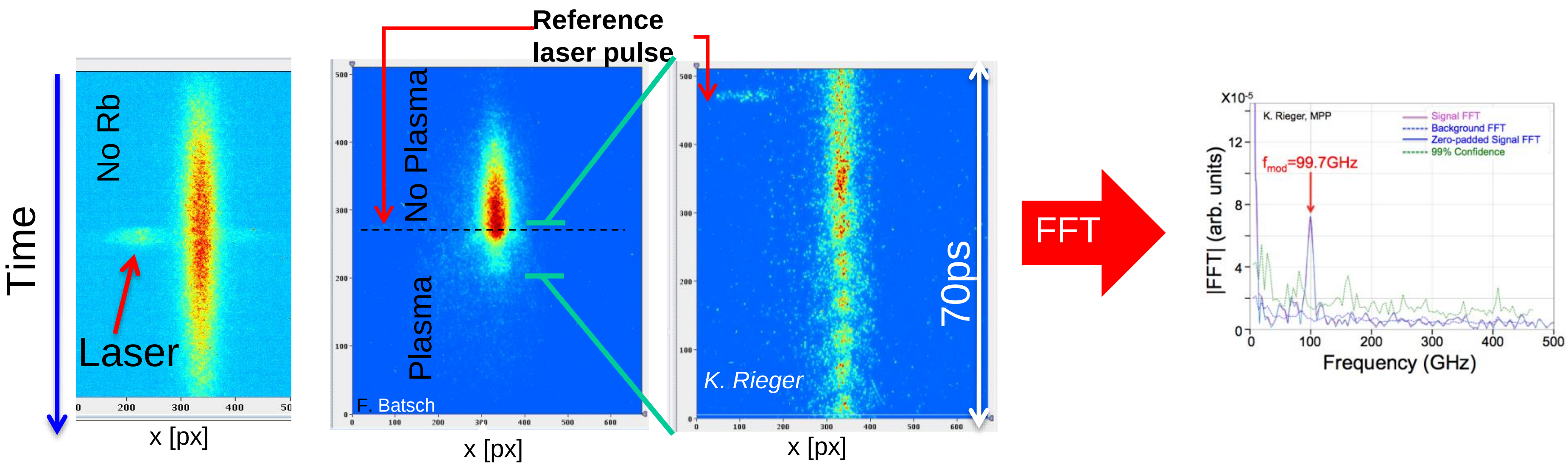




1st AWAKE-goal: SSM

OTR on streak camera:

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



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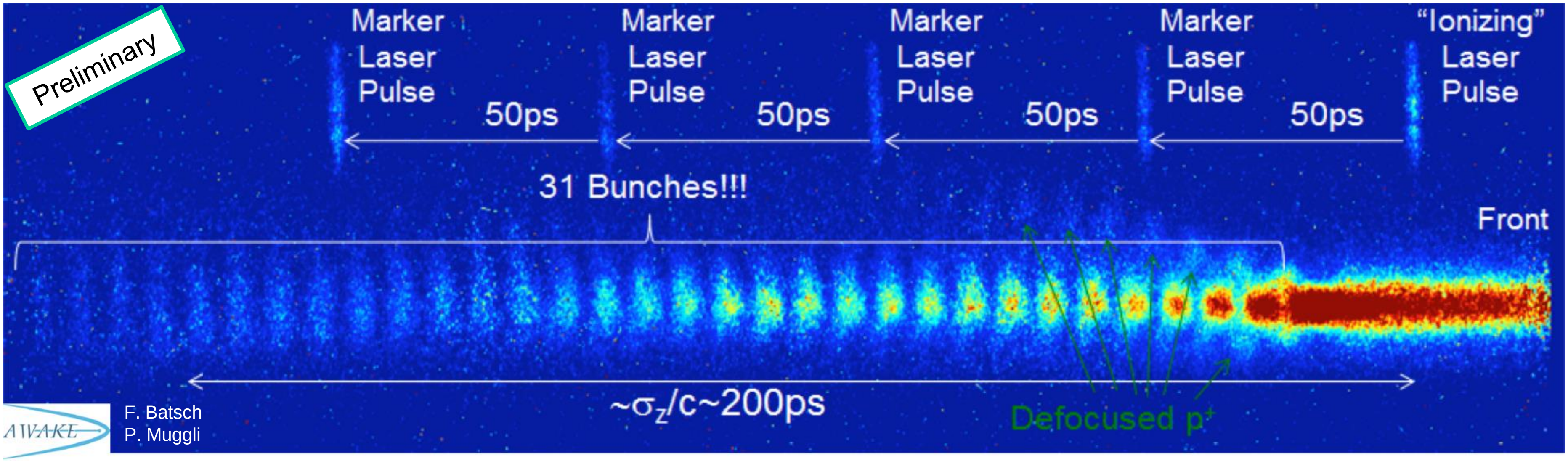
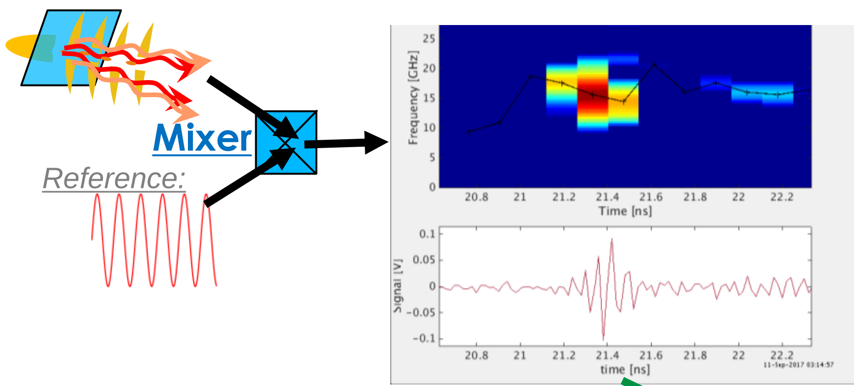
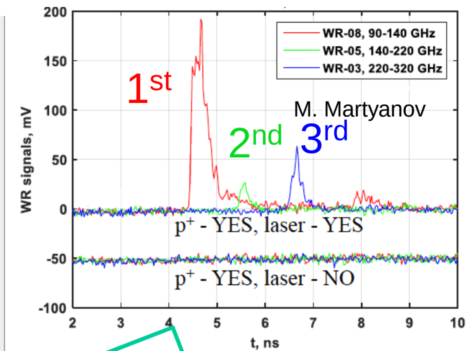
1st AWAKE-goal: SSM

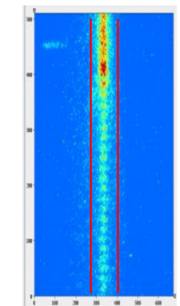
- Microbunches reach all the way along p^+-bunch! (good for e^- acceleration)
- Overlayed pictures ➔ Very phase-stable & reproducible!!



1st AWAKE-goal: SSM





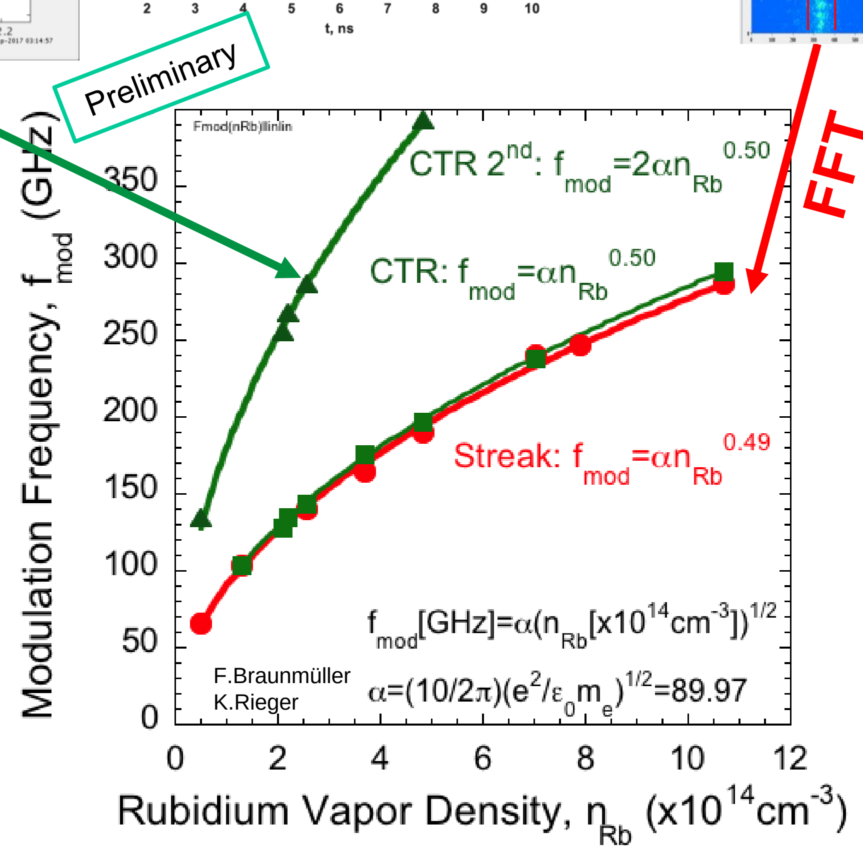


CTR and OTR frequency measurement:

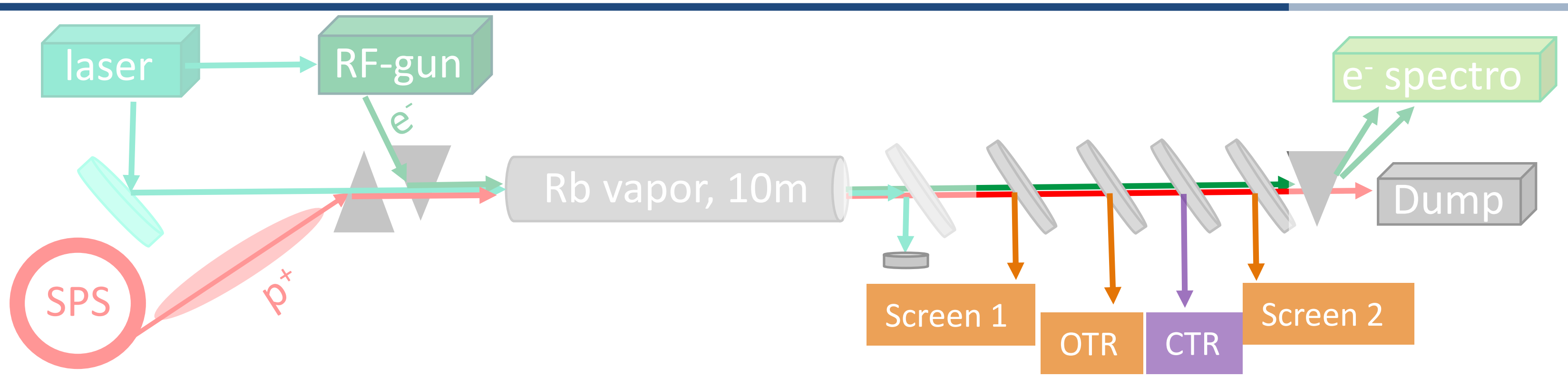
- Precisely matching expected plasma frequency (vs. measured **vapour** density)
  $f_{mod} \sim f_{plasma}(n_{Rb})$

➔ ~100% singly ionized Rb-plasma

➔ SSM with expected behaviour



1st AWAKE-goal: SSM



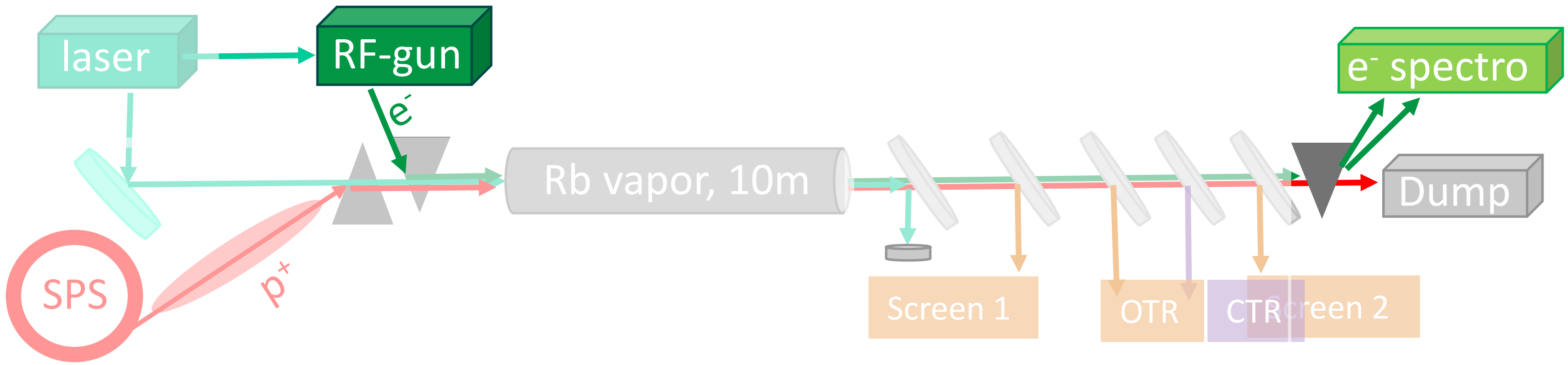
2016-17

- 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

2nd AWAKE-goal : e⁻-acceleration

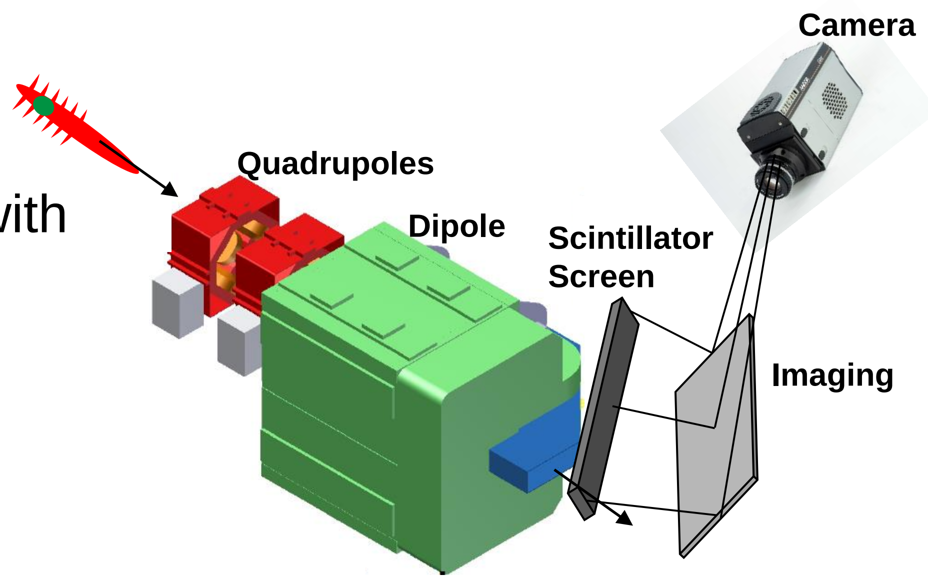


2017-18

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

- Diagnostics:

Electron spectrometer



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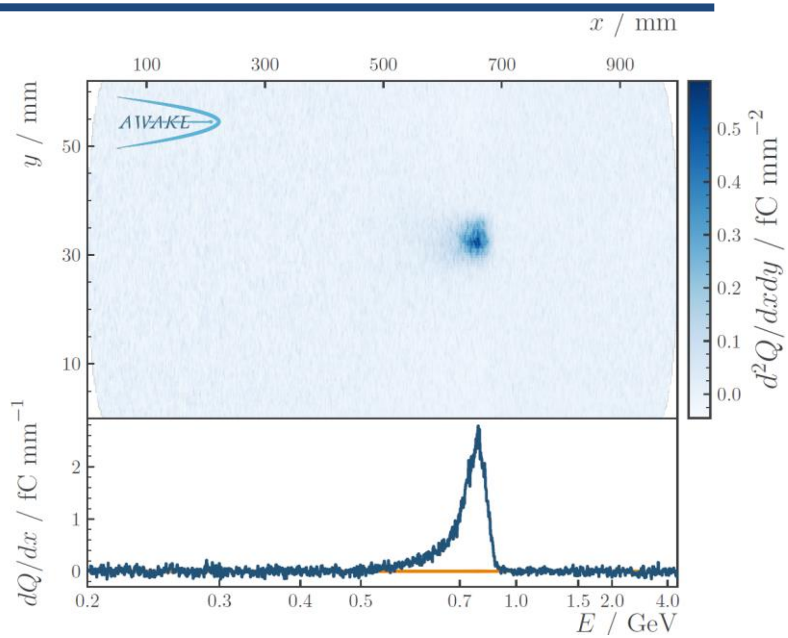
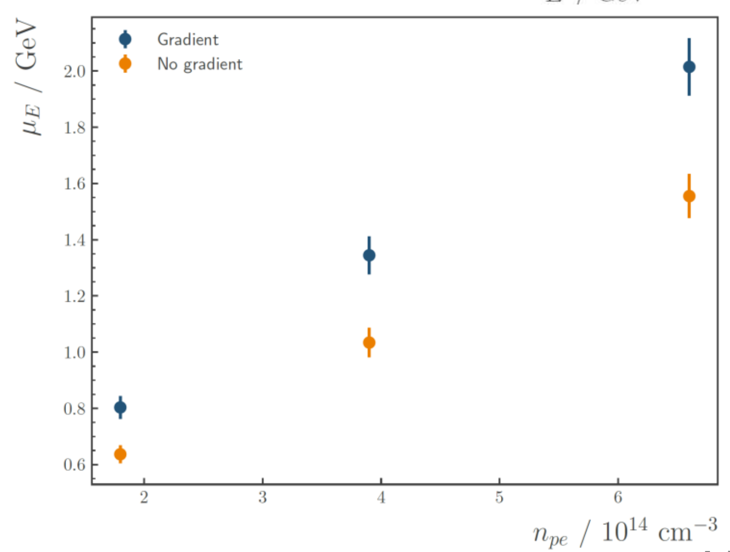
2nd AWAKE-goal : e⁻-acceleration

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, capture <2%)
- Narrow energy-distribution & quite stable
- Best Accelerating field ~100MeV/m-GeV/m





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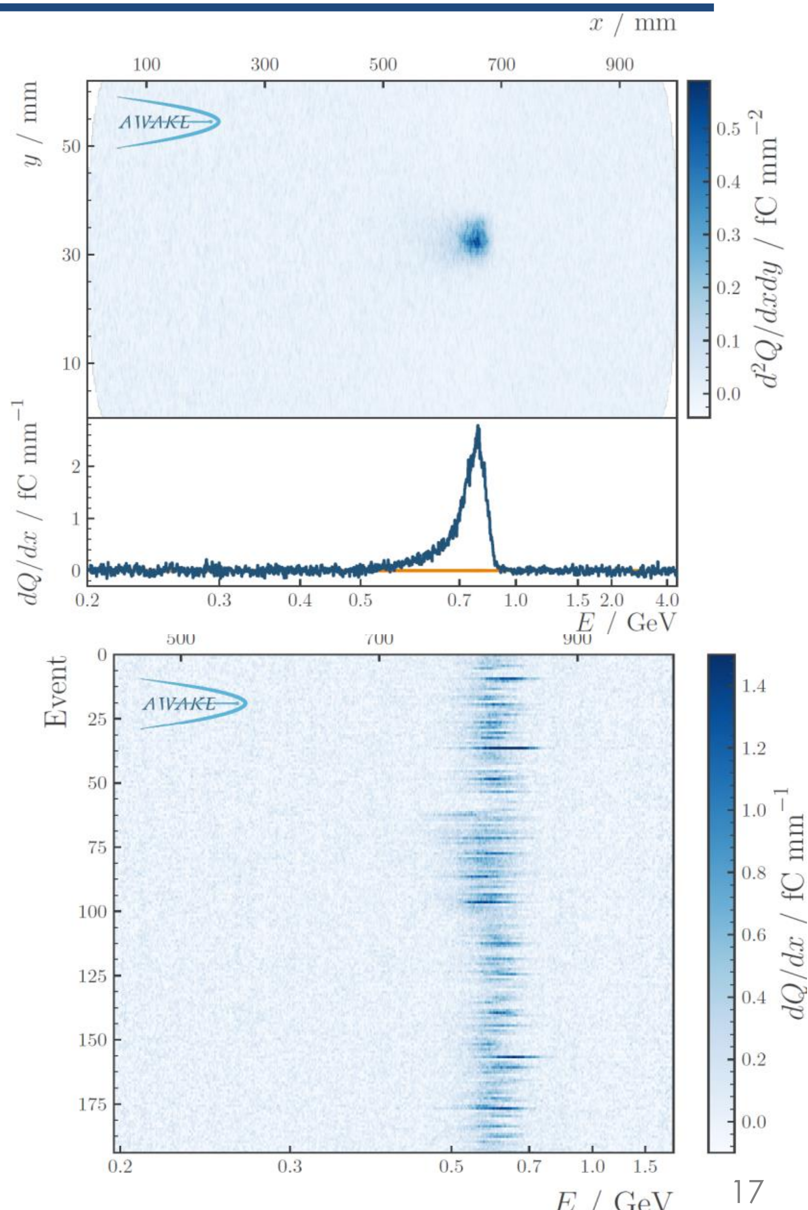
2^{nd} AWAKE-goal : e^--acceleration

2017-18

2^{nd} goal: accelerate e^-s in self-modulated p^+-bunch ✓

- **First acceleration of e^-s with p^+-driven PWFA: up to 2GeV!!**
  (injected ~19MeV, capture <2%)
- Narrow energy-distribution & quite stable
- Best Accelerating field ~100MeV/m-GeV/m



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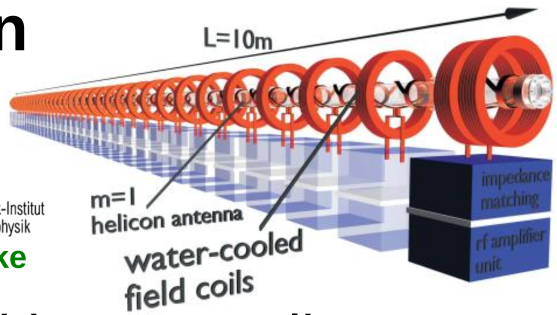
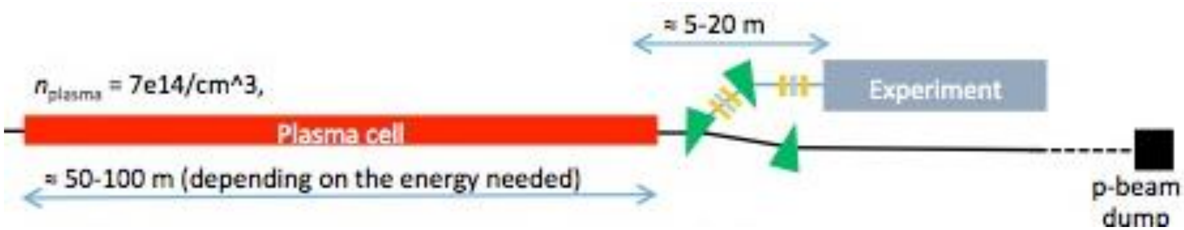
AWAKE Run II

- **Injection AFTER modulation:**
  Split SSM-stage + ~10m acceleration



  - 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



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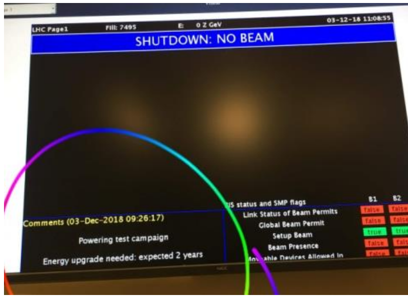
Summary

- **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$^-$'s for first time with p$^+$-driven PWFA
  (2GeV/~10pC)

Future:



- **Long shutdown: prepare Run II**
- **Run II: SSM-stage + acceleration stage → ~10GeV**
  → fixed target

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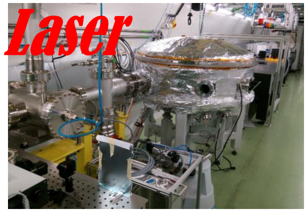
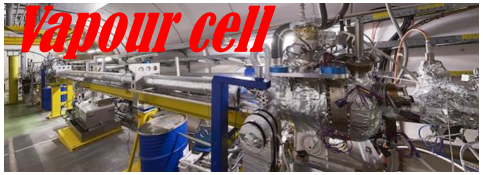
MPP-contribution

- **Initiated by MPP-group**
- **Continuing leadership in collaboration with CERN**

Group leaders:
Allen Caldwell
Patric Muggli

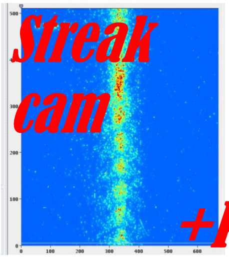


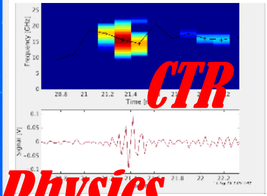
Post-Docs:
Joshua Moody
Mikhail Martyanov
Falk Braunmüller
Erdem Öz (left)



PhD-students
Matthias Hüther
Anna-Maria Bachmann (Ex-MPP, LMU-affiliated)
Fabian Batsch (Ex-MPP, LMU-affiliated)
Karl Rieger (left)

Master/Bachelor student:
Felipe Peña Asmus





AWAKE Collaboration

THANK YOU!!!

Thanks for your attention!

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

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Additional slides

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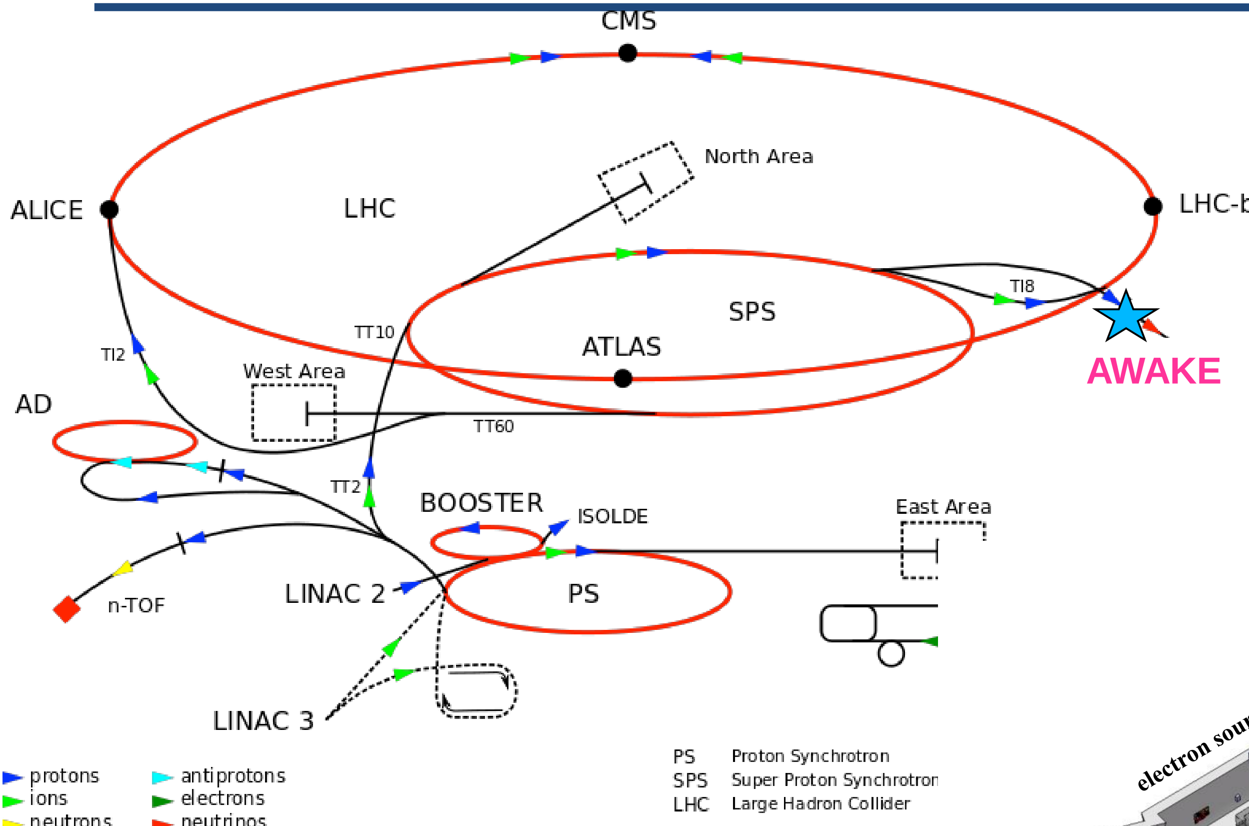
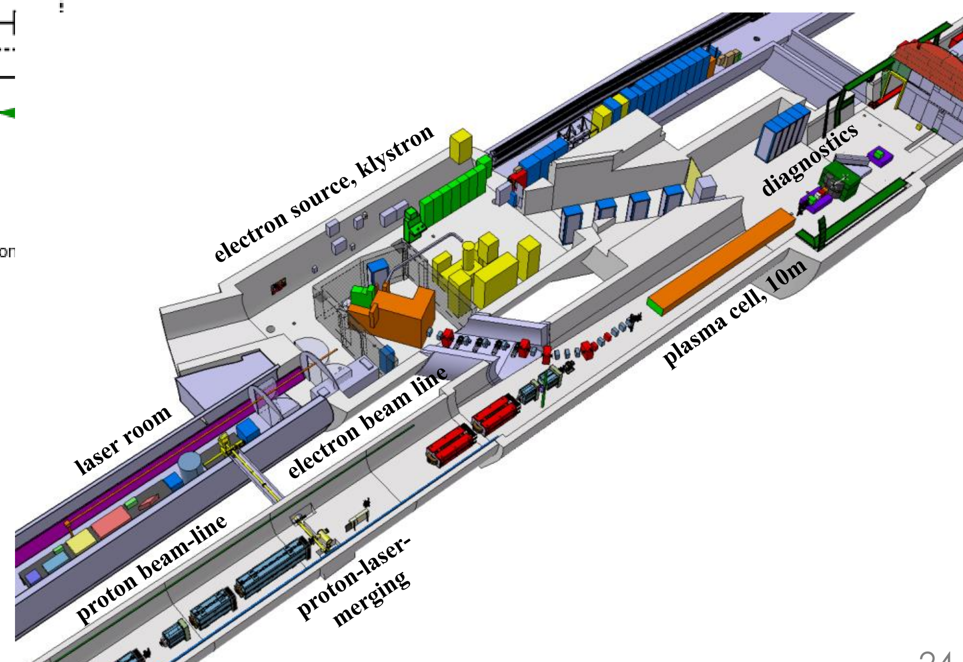
AWAKE @ CERN



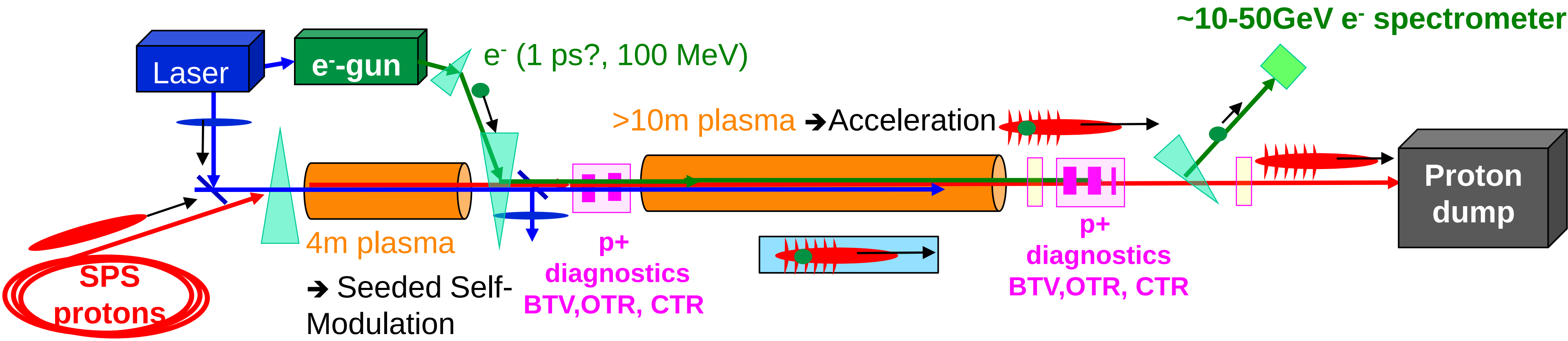
- SPS-proton bunch (400GeV): ~19kJ;
- LHC-bunch (13TeV): ~112kJ

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

SPS: 400GeV, $3 \cdot 10^{11}$ p^+,
σ_r ~ 0.2mm, σ_z ~ 12cm
➔ **self-modulation**

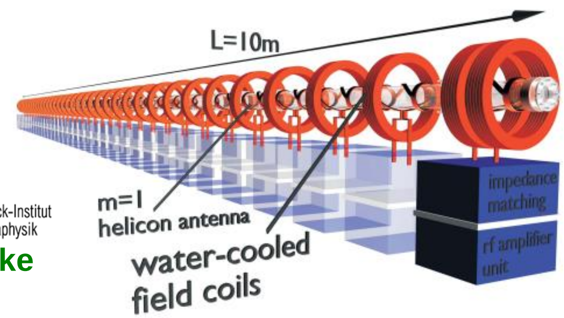


AWAKE Run II



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

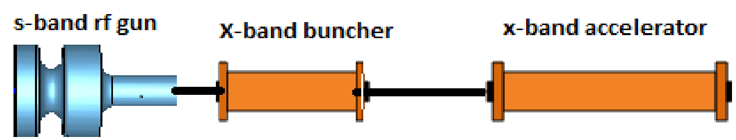
Helicon-plasma (scalable to 100s of meter)



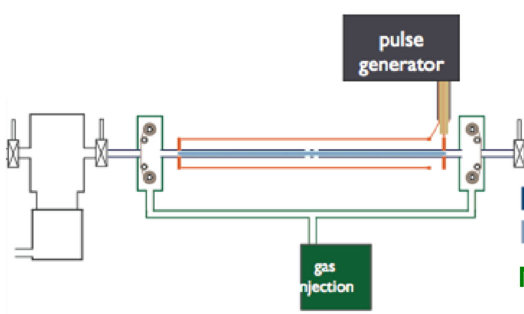
IPP Max-Planck-Institut für Plasmaphysik

O. Grulke

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



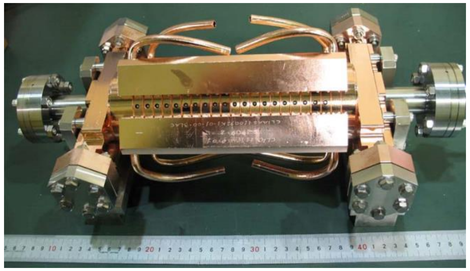
Discharge source 10m



TÉCNICO LISBOA

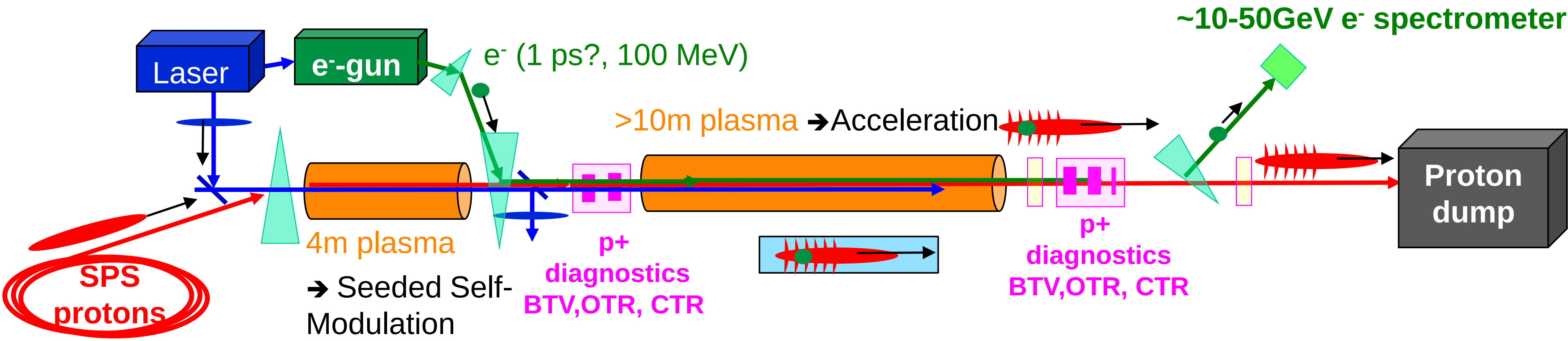
Imperial College London

N. Lopez

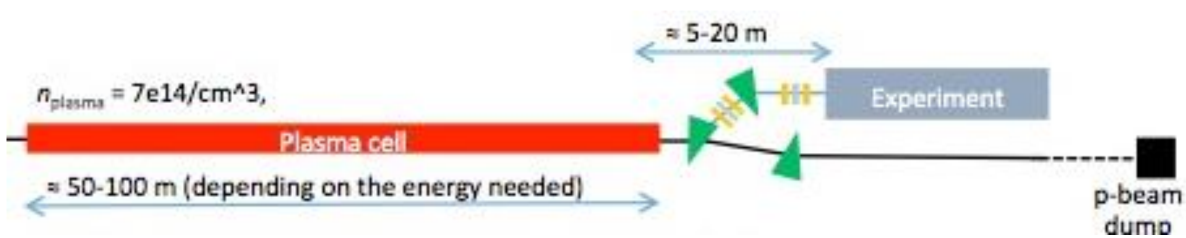


S. Döbert, CERN

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



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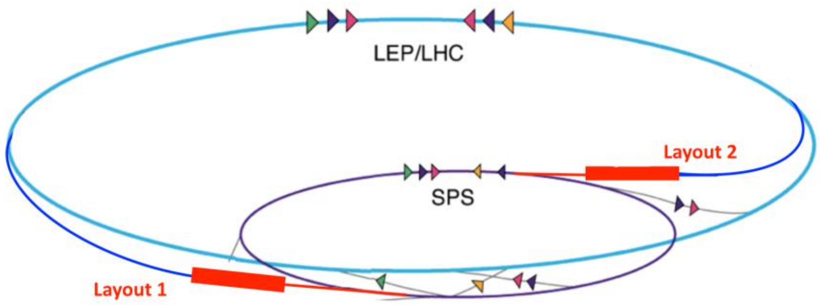
Application: e^{-}-p^{+} collider @ LHC ?

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

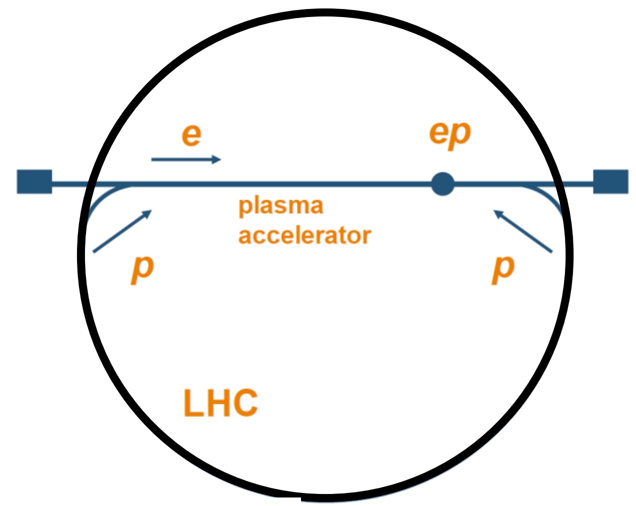
- Create ~50 GeV e^{-}-beam within 50−100 m of plasma driven by SPS protons → large cross-sections/low luminosity
- Already E_e = 10 GeV, E_p = 7 TeV, $\sqrt{s}$ = 530 GeV exceeds HERA cm energy

Option 2: LHC-driven accelerator

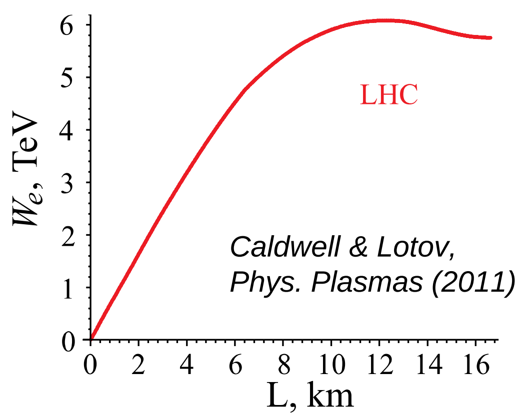
- E_e = 3 TeV vs. E_P = 7 TeV yields $\sqrt{s}$ = 9 TeV (~30 higher than HERA)



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

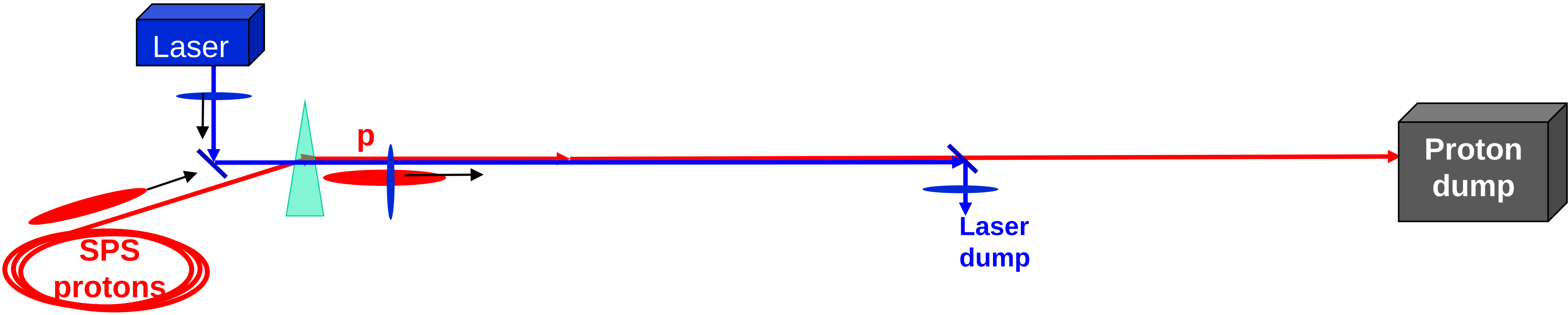


Caldwell & Wing, Eur. Phys. J. C (2016) 76



Caldwell & Lotov, Phys. Plasmas (2011) 18

Experimental setup

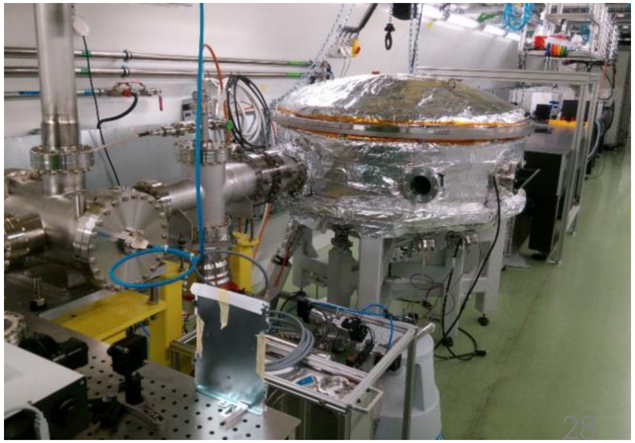


p^+ from SPS:
with chicane for merging

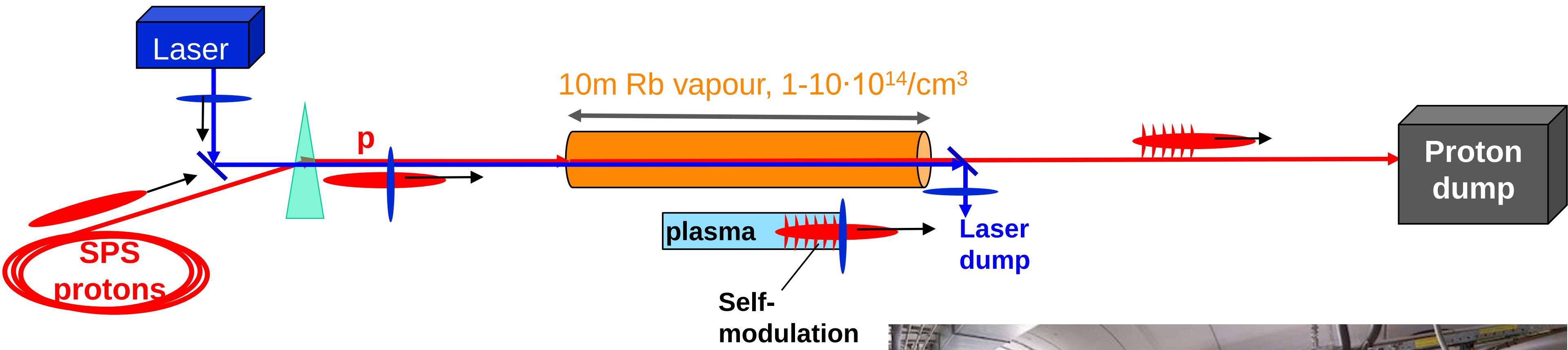
- Ionizing laser:

Fiber/Ti-Sapphire laser:
~100fs, E_{max}=450mJ,
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

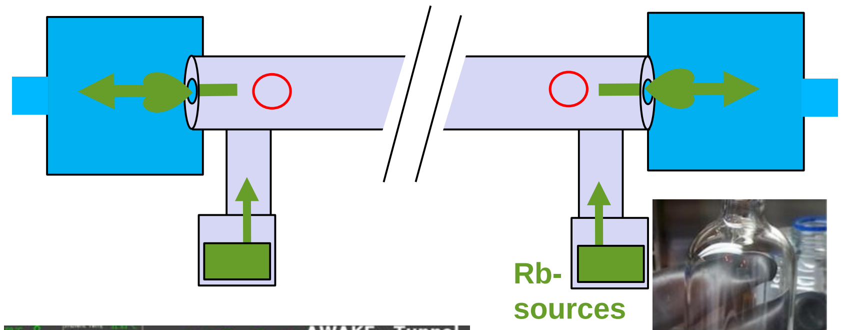


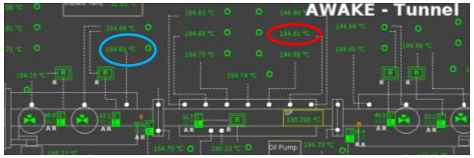
Experimental setup



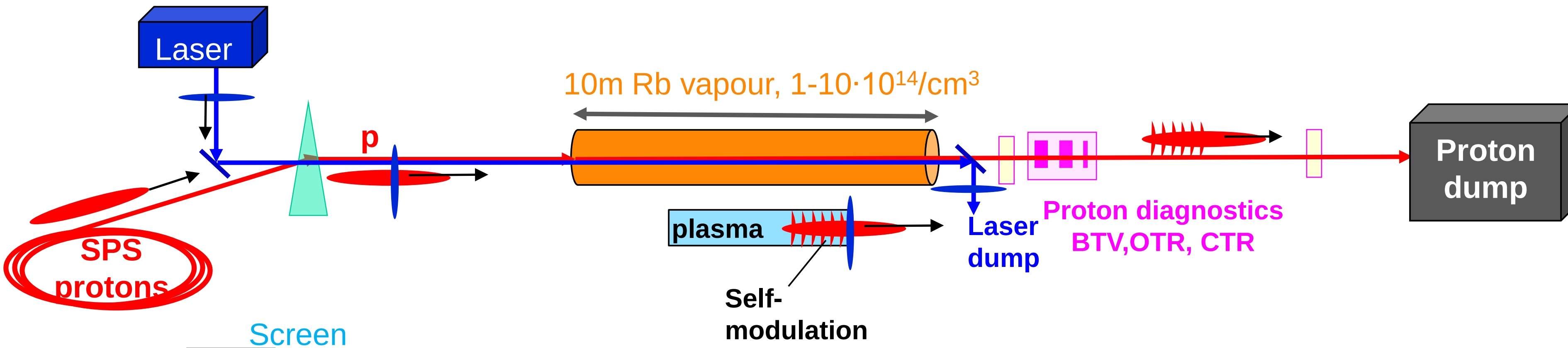
10 m Rubidium vapour cell

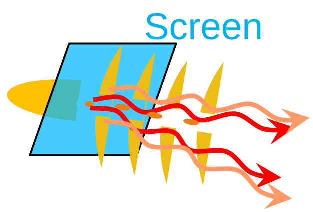
- Plasma density-requirement: $1\text{-}10\cdot10^{14}/cm^3$ + uniformity $\Delta n_e/n_e<0.2\%$
  ↓
  10 m oil bath, Rb @ 160-220°C
- Evaporation → flow → condensation
- Density-measurement: white-light interferometry
  ➔ accuracy <0.3%
  ➔ Gradient controlled via $T_{Rb\text{-}source}$ (<0.3%/10m)
- Beamline (ripples):
  $\Delta T/T = \Delta n_{Rb}/n_{Rb} \sim 0.15°C^{\text{measured}}/500K = 0.03\%$!!





Experimental setup



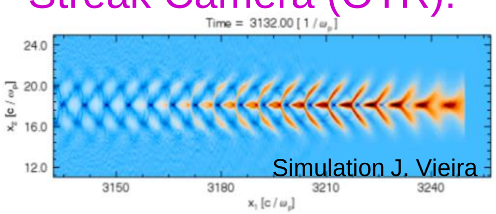


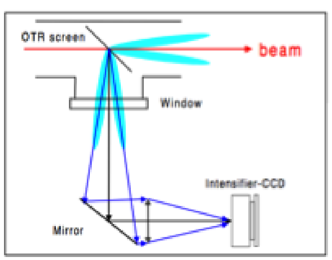
Modulated p+
→ coherent/optical TR
(CTR/OTR)

CTR-diagnostics:

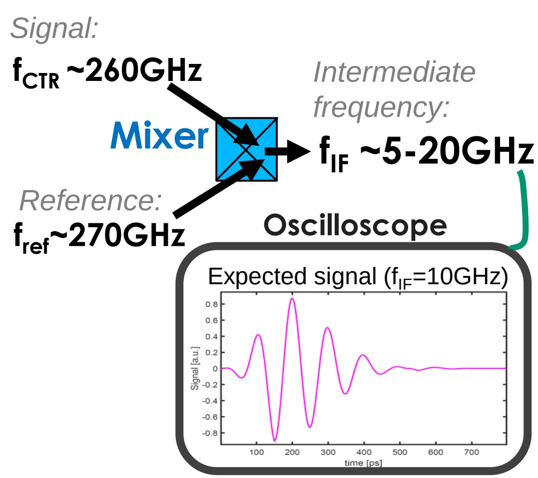
Coherent transition radiation @ $f_{modulation}$ (90-280GHz)

Streak Camera (OTR):

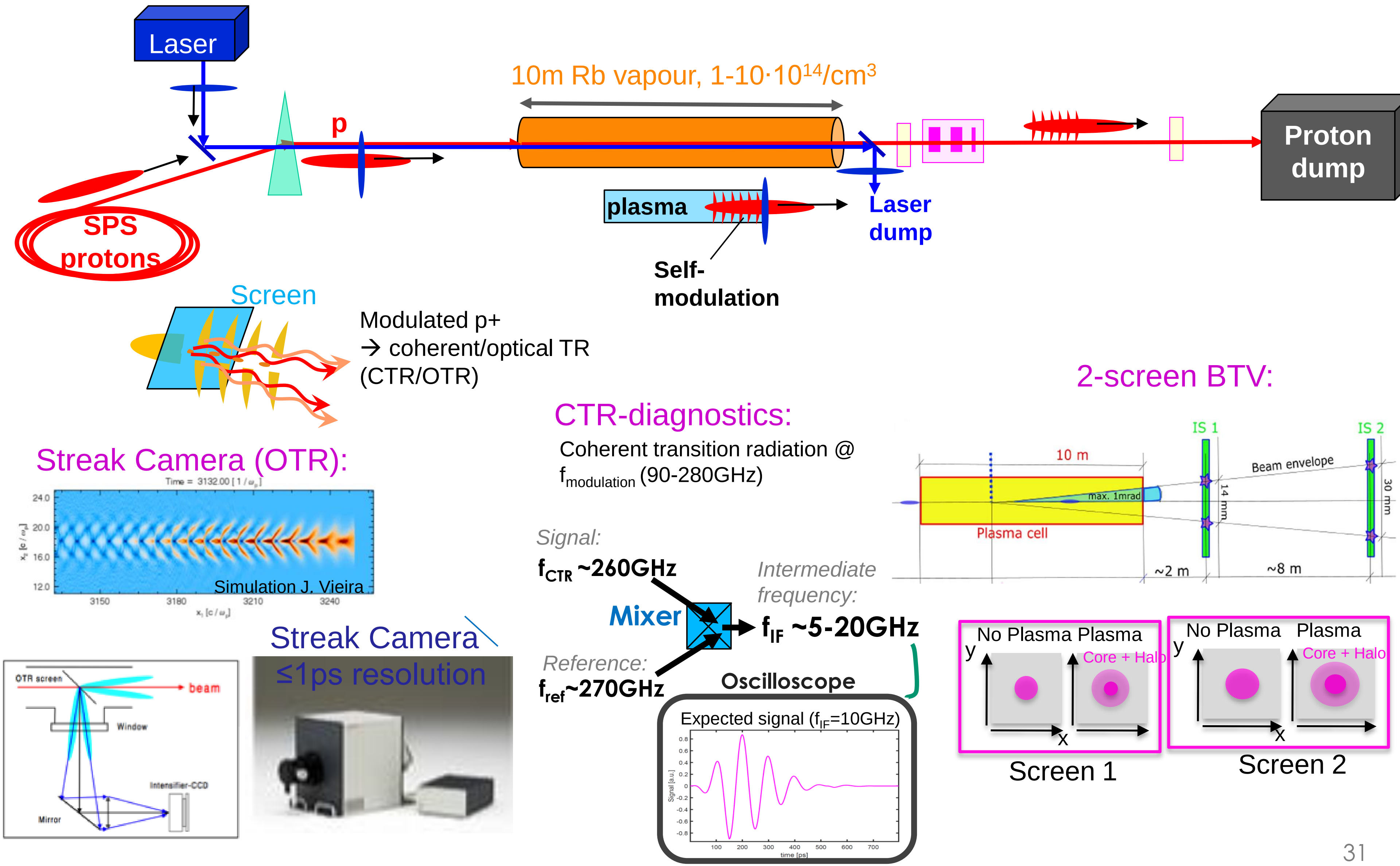




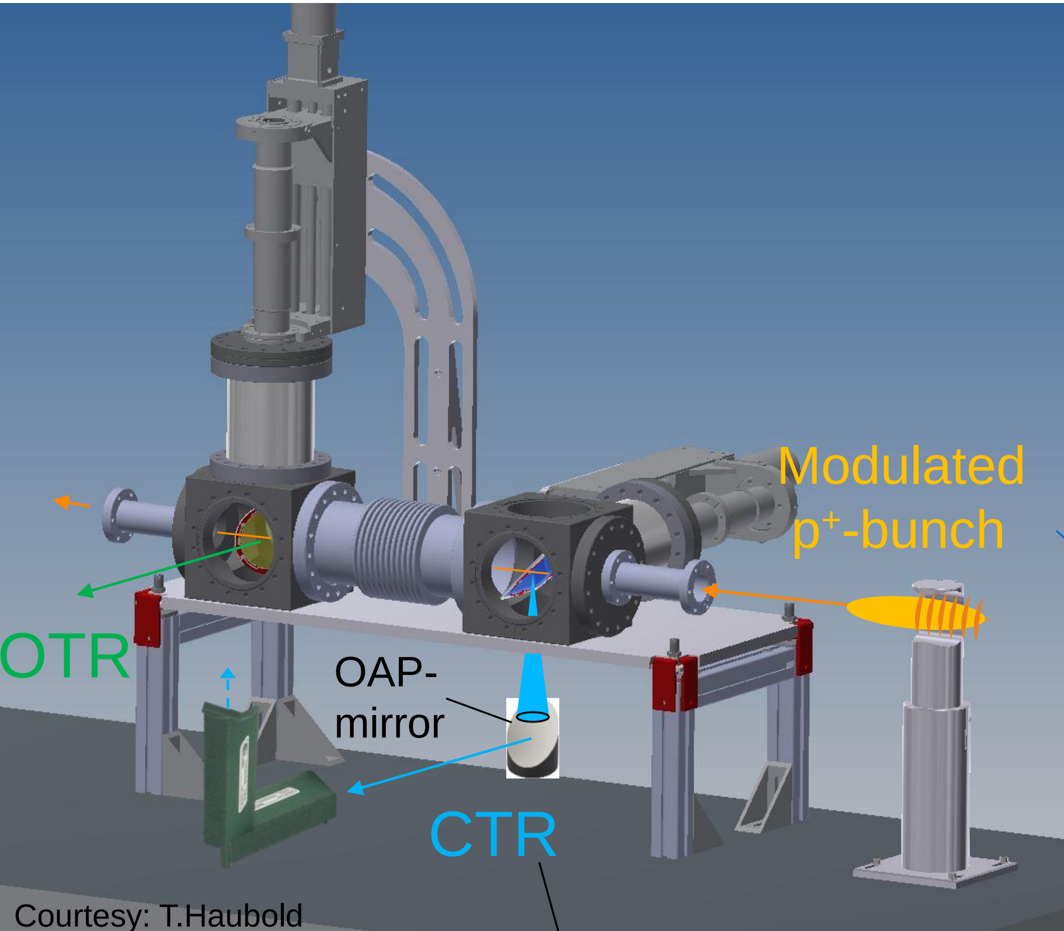
Streak Camera
≤1ps resolution

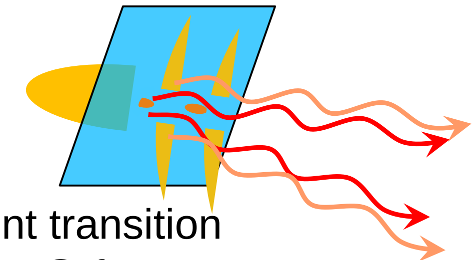


Experimental setup



SSM-Diagnostics via CTR





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

Signal:

f_{CTR} ~260GHz

Reference:

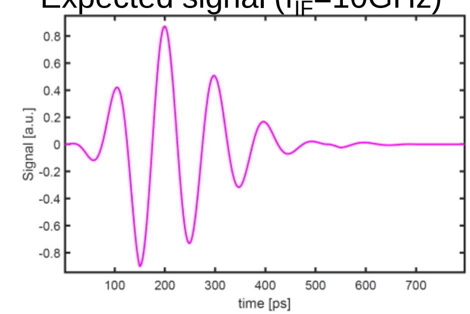
f_{ref}~270GHz

Mixer

Intermediate frequency:

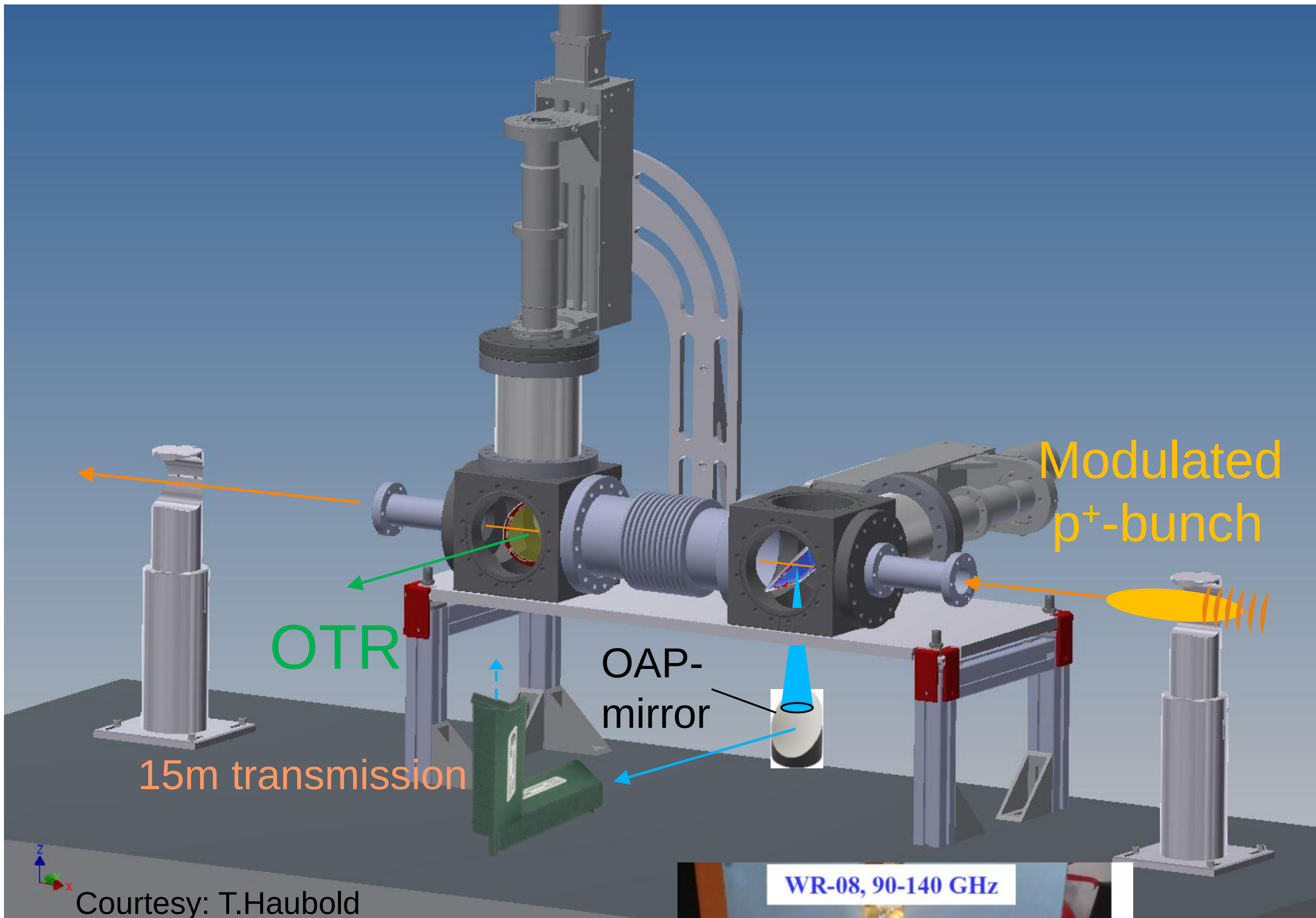
f_{IF} ~5-20GHz

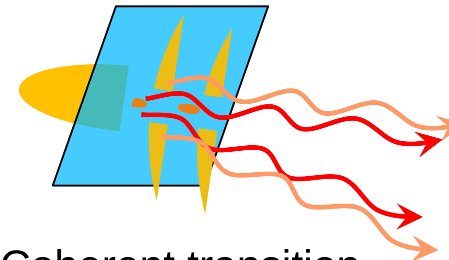
Expected signal (f_{IF}=10GHz)



Coupled into WR90 waveguide →15m transmission

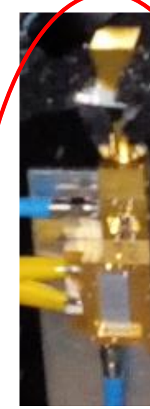
SSM-Diagnostics via CTR



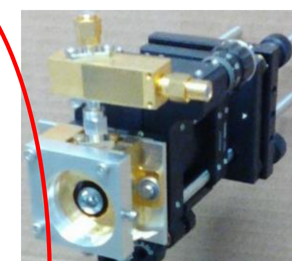


Coherent transition radiation @ $f_{modulation}$ (90-280GHz)

Frequency:
Heterodyne mixing



Waveguide-based



Laser-based

Amplitude:
Schottky diodes

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Diagnostic setup

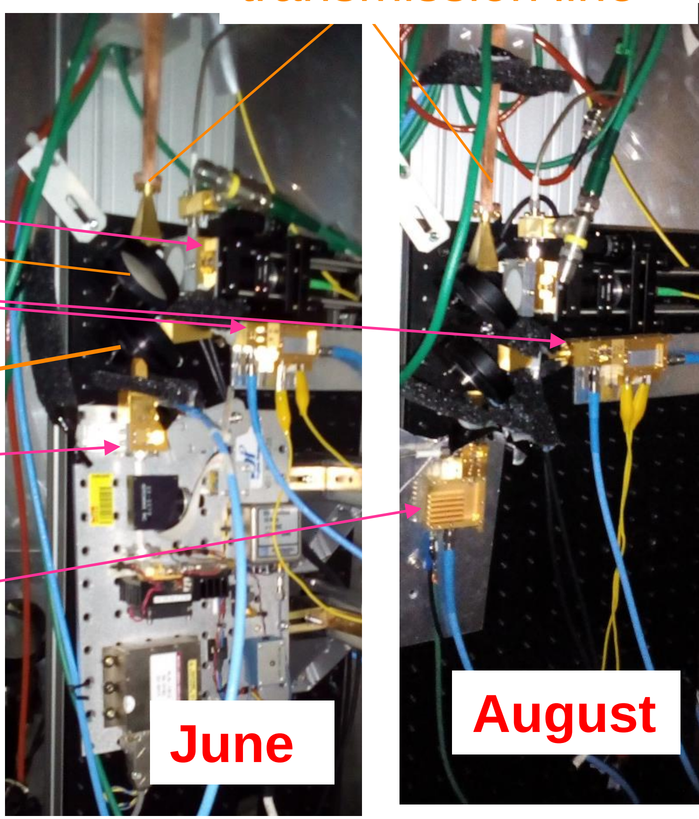
- **3 Heterodyne receivers for CTR:**
  - **Laser-based mixing** **(last presentation)**
  - **WR8 / 90-140GHz: Radiometer-system**new
  - **WR3.4 / 255-270GHz: VDI-system from EPFL**

  ↳ **replaced by WR4.3/170-260GHz system**
- **Can detect 2nd harmonics of $f_{modulation}$**

End of
transmission line

Mirror

Beam splitter



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Results of CTR-analysis

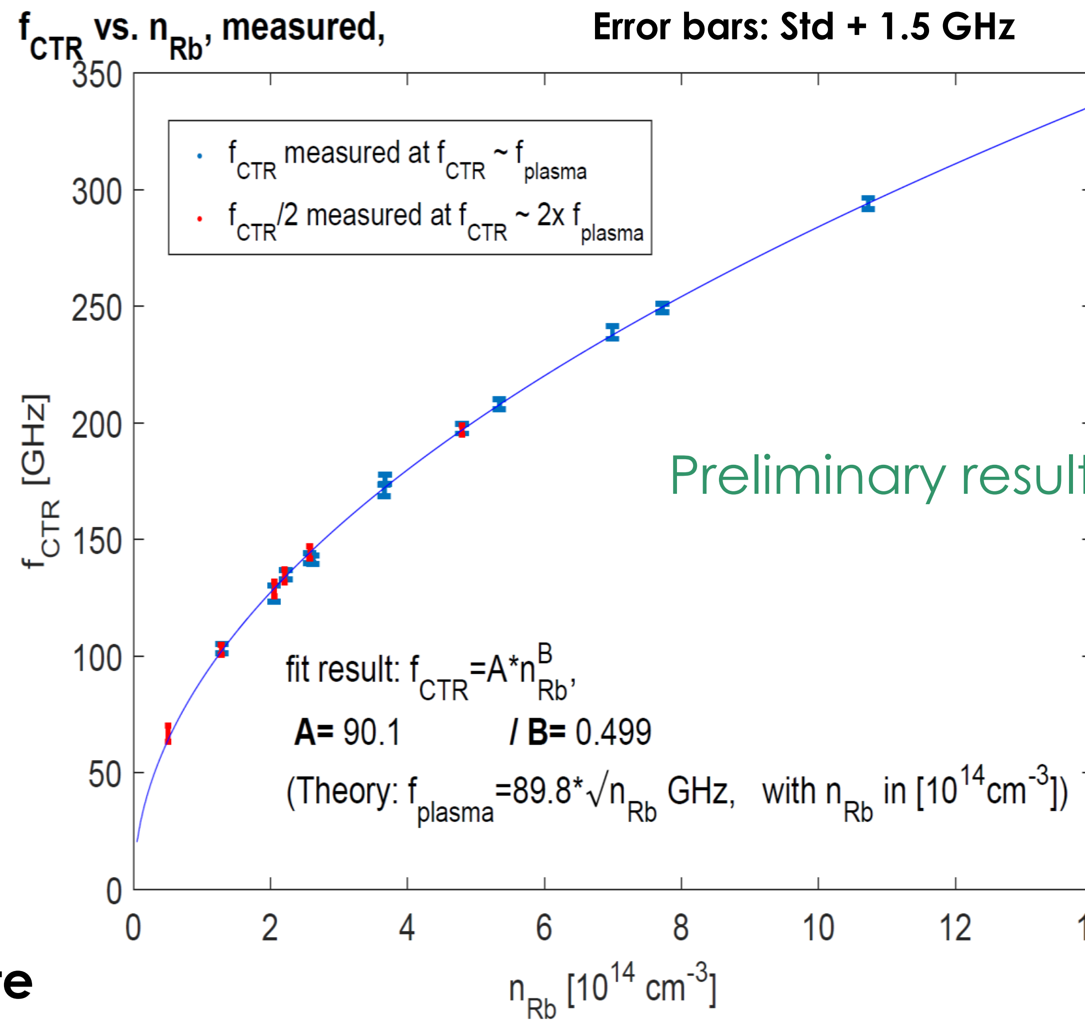
Result: f_{CTR} vs. n_{RB} ← vapour

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

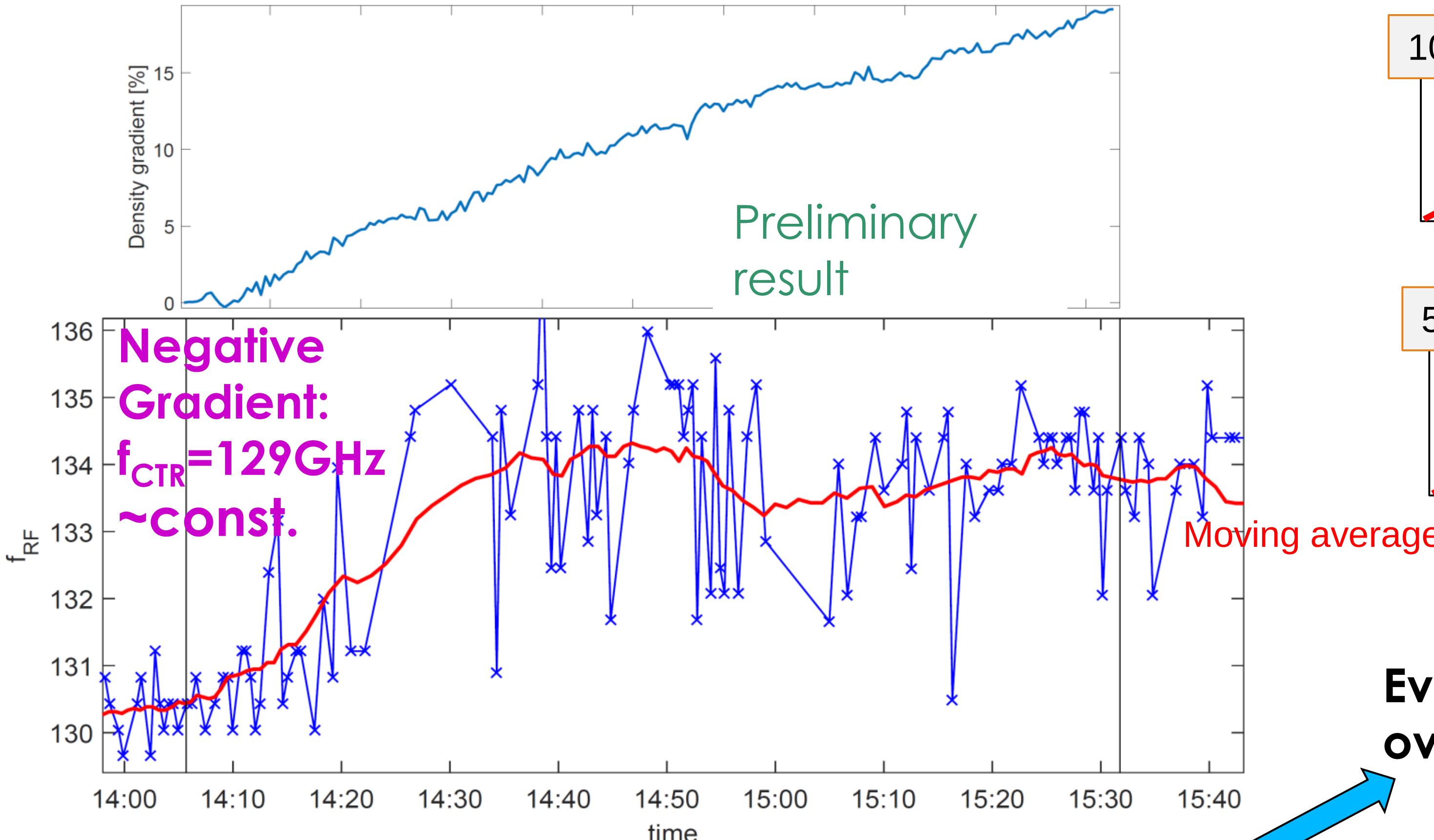
- ➔ SSM with f_{CTR}=f_{plasma} as predicted
- ➔ Rb fully ionized
- Good match between fundamental & 2nd harmonics

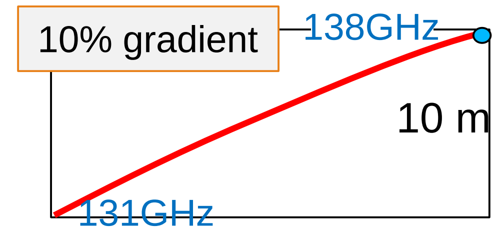
→ proof that correct $n_{harm}(f_{LO})$ was chosen

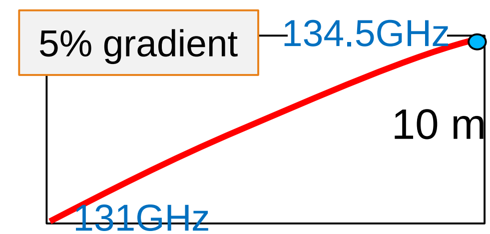
- Excellent fit result: parameters within 0.3%
- Error analysis incomplete



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?

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