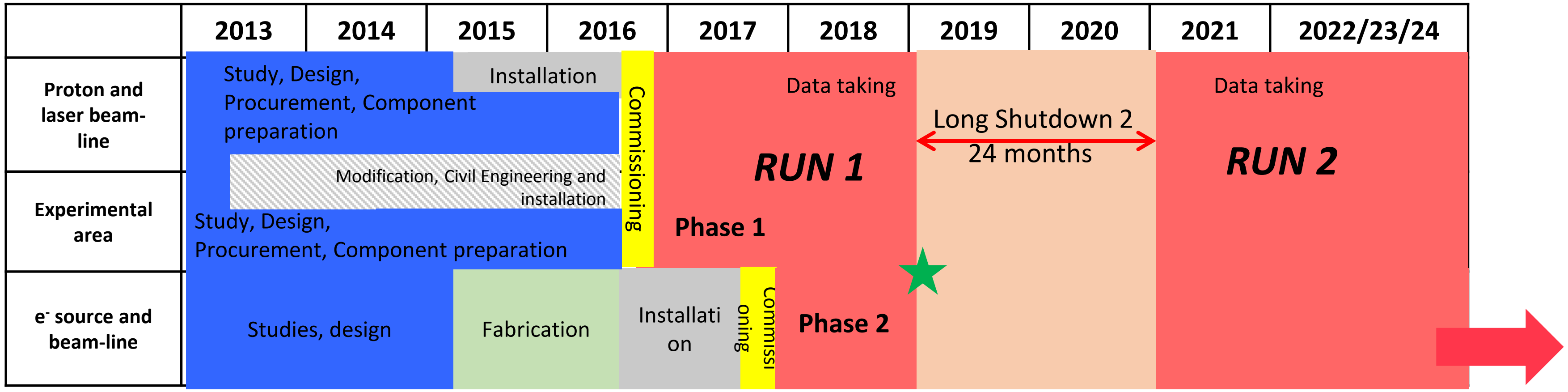
AWAKE Commissioning

Edda Gschwendtner, CERN

MSWG 6 April 2018

Introduction



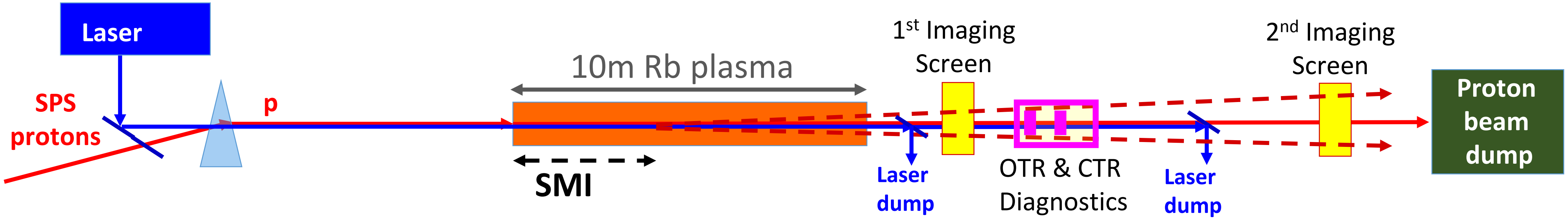
Run 1: 1st milestone reached of Seeded Self-Modulation of Proton beam in Plasma
2018: 2nd milestone: electron acceleration in plasma → high expectations!

After LS2 – proposing Run 2 of AWAKE (during Run 3 of LHC)
→ depends on electron acceleration run 2018!
→ Prepare a Run 2 design report by 2018/19 for approval ★

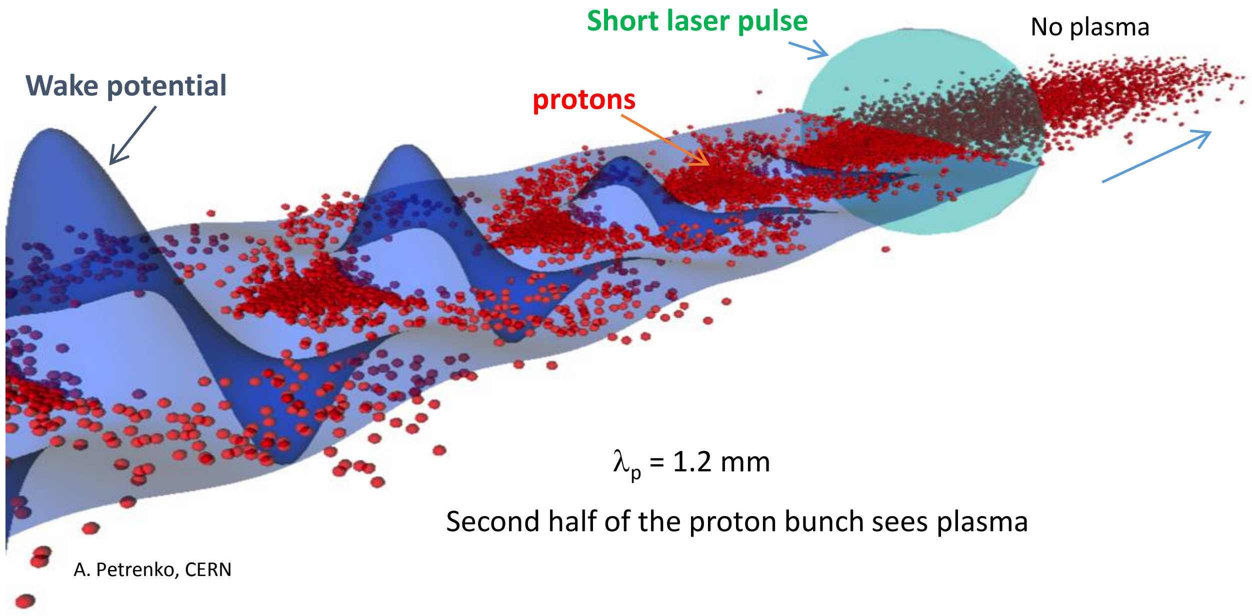
After Run 2: kick off particle physics driven applications → PBC

First Experiment: Seeded Self-Modulation

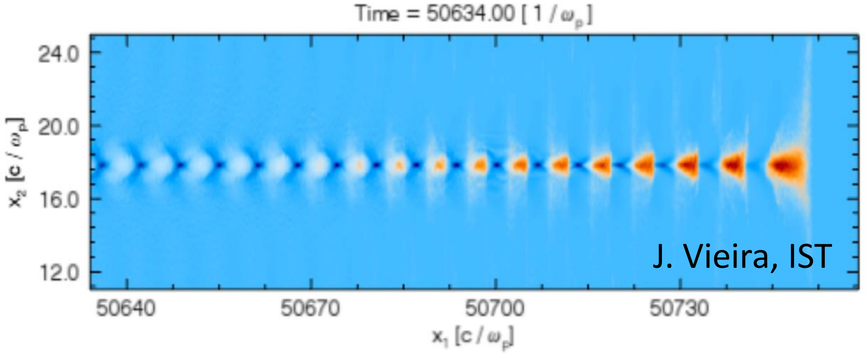
Phase 1: 2016/17: Understand **the physics of self-modulation instability** processes in plasma.



Self-modulated proton bunch resonantly driving plasma wakefields.



What we want to see in the diagnostics:

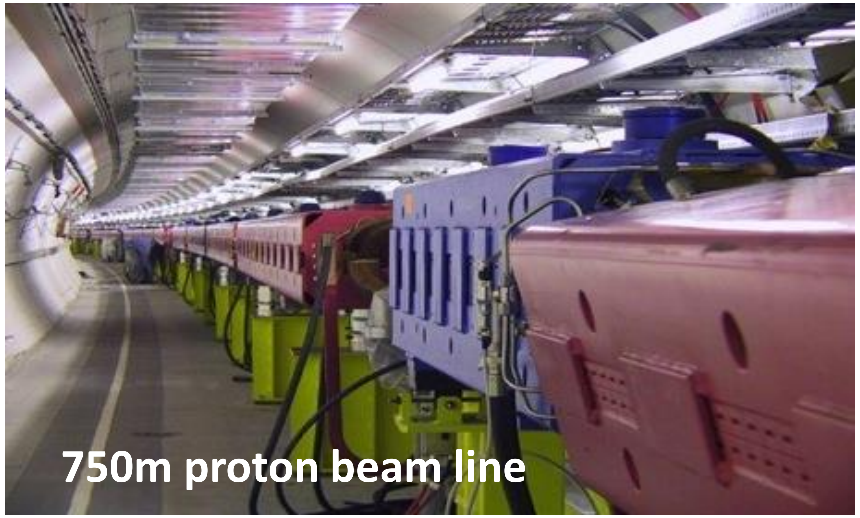


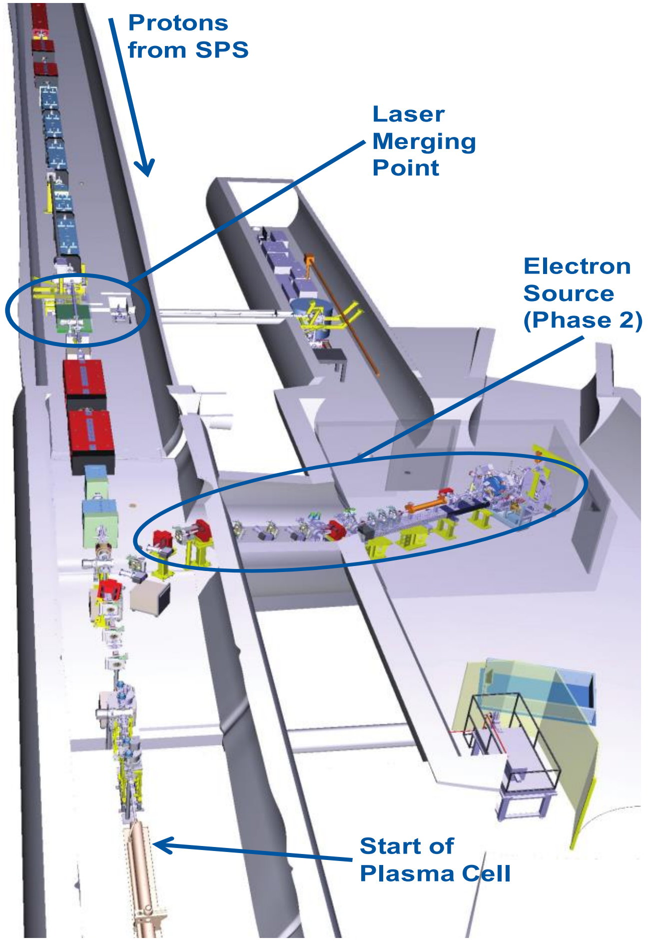
AWAKE Proton Beam Line

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

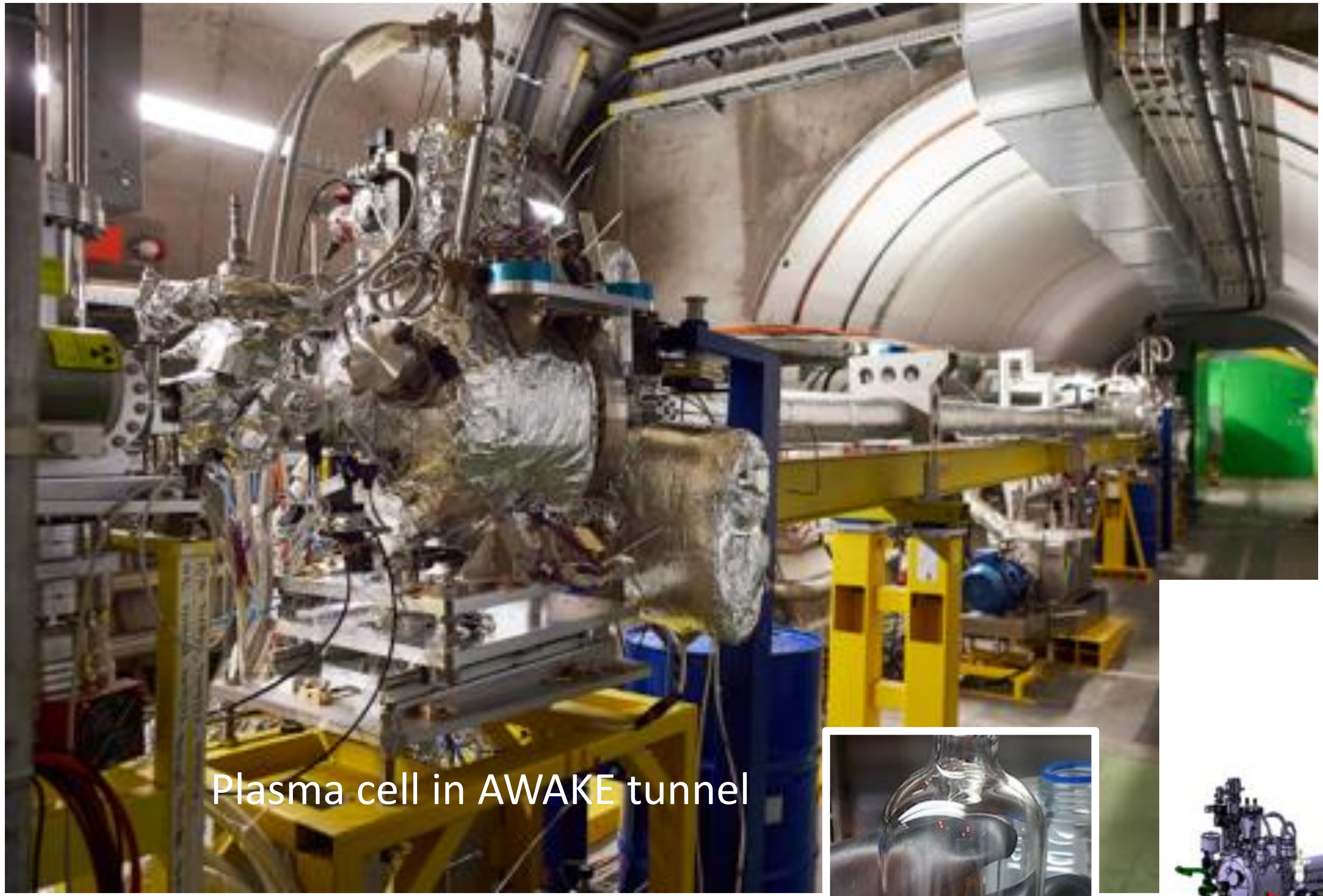
First experiment: Measure seeded self-modulation!

Plasma linear theory: $k_{pe}\, \sigma_r \leq 1$
with $n_{pe} = 7 \times 10^{14}\ cm^{-3}$
$k_{pe} = \omega_{pe}/c = 5\ mm^{-1}$
➔ **$\sigma_r = 200\ \mu m$**





The AWAKE Plasma Cell


Plasma cell in AWAKE tunnel

→ 10 m long, 4 cm diameter

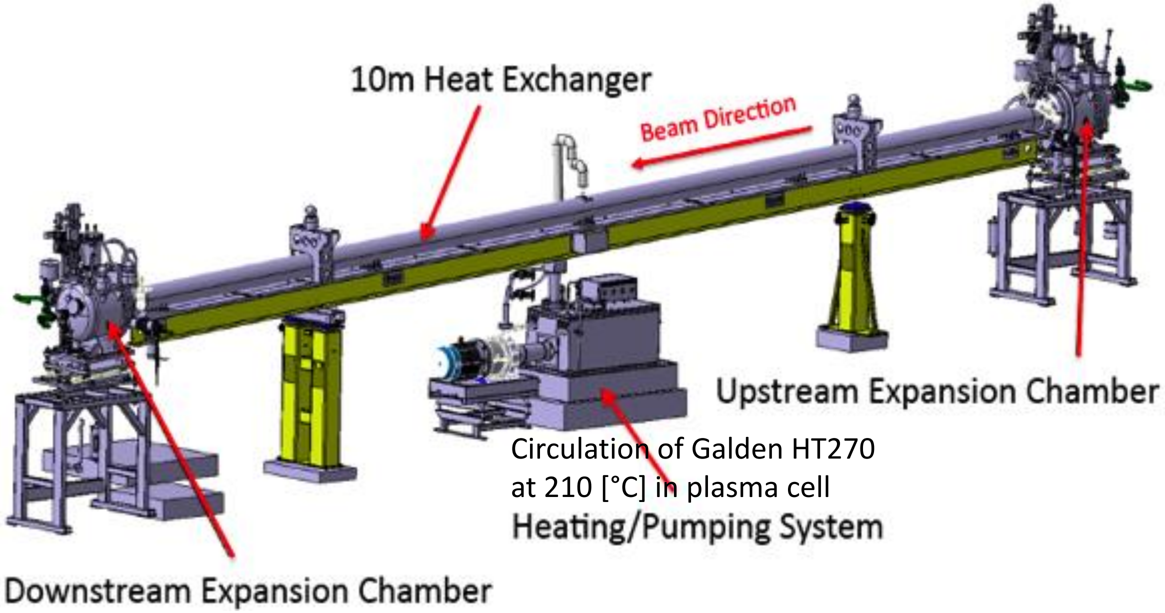
→ Rubidium vapor

→ Laser field ionization: threshold ~10^{12} W/cm^2

→ Rb density measured with 0.3% accuracy using white light interferometry

Requirements:

- Density adjustable from 10^{14} – 10^{15} cm^{-3} (7×10^{14} cm^{-3})
- $\Delta n_e/n_e$ density uniformity better than 0.2%
- few cm n_e ramp: transition between plasma and vacuum as sharp as possible

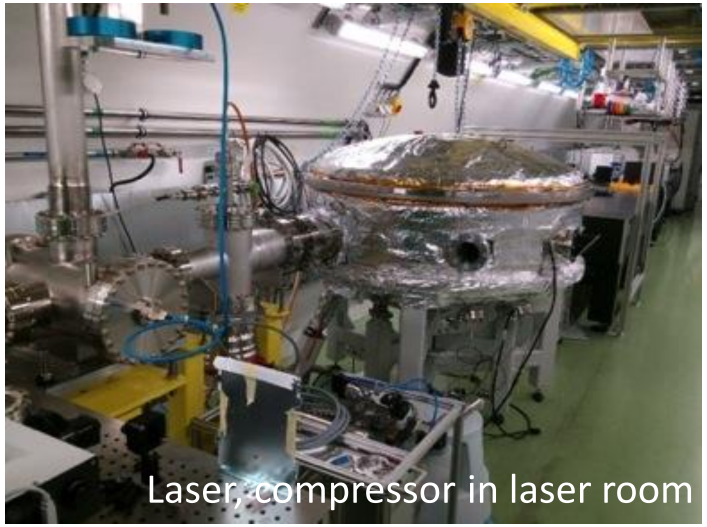


Laser and Laser Line

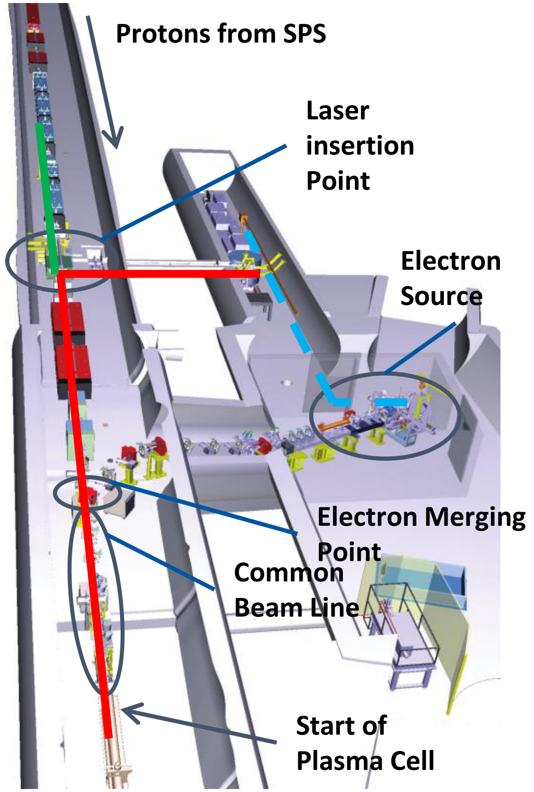
V. Fedosseev, F. Friebel, CERN
J. Moody, M. Huether, A. Bachmann, MTP

Fiber/Ti-Sapphire laser

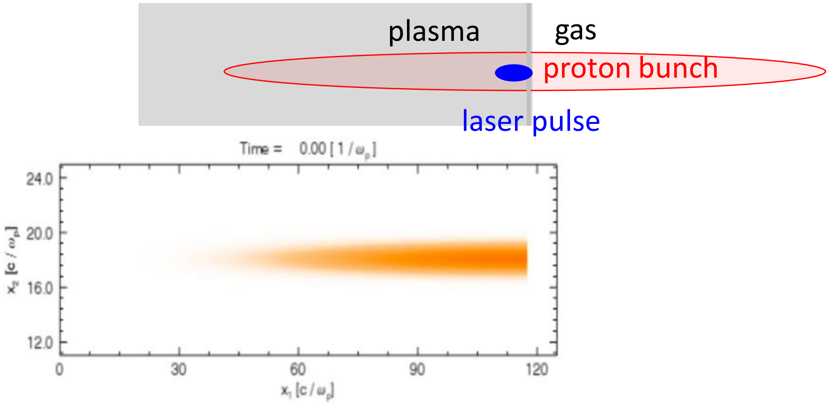
- **Laser beam line to plasma cell**
  - λ = 780 nm, t_{pulse} = 100-120 fs, E = 450 mJ
- **Diagnostic beam line ("virtual plasma")**
- ***Laser beam line to electron gun***



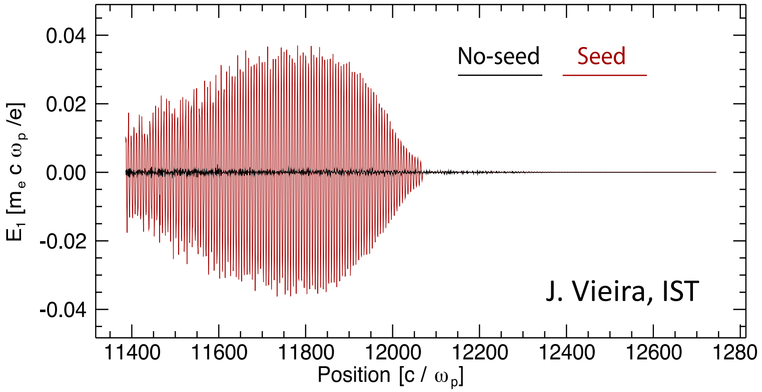
Laser, compressor in laser room



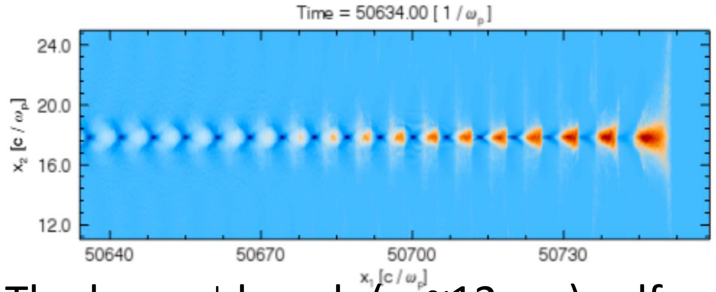
➔ **Short laser pulse creates the plasma and seeds the SSM**



Sharp start of beam/plasma interaction
→ Seeding with ionization front

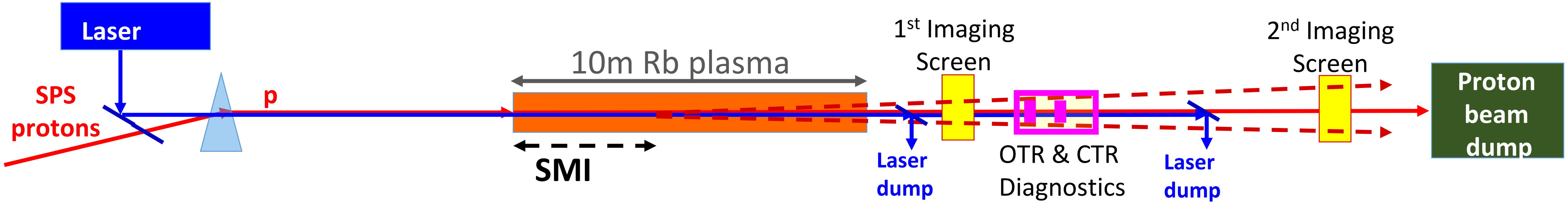


No seed no SM (over 10m)



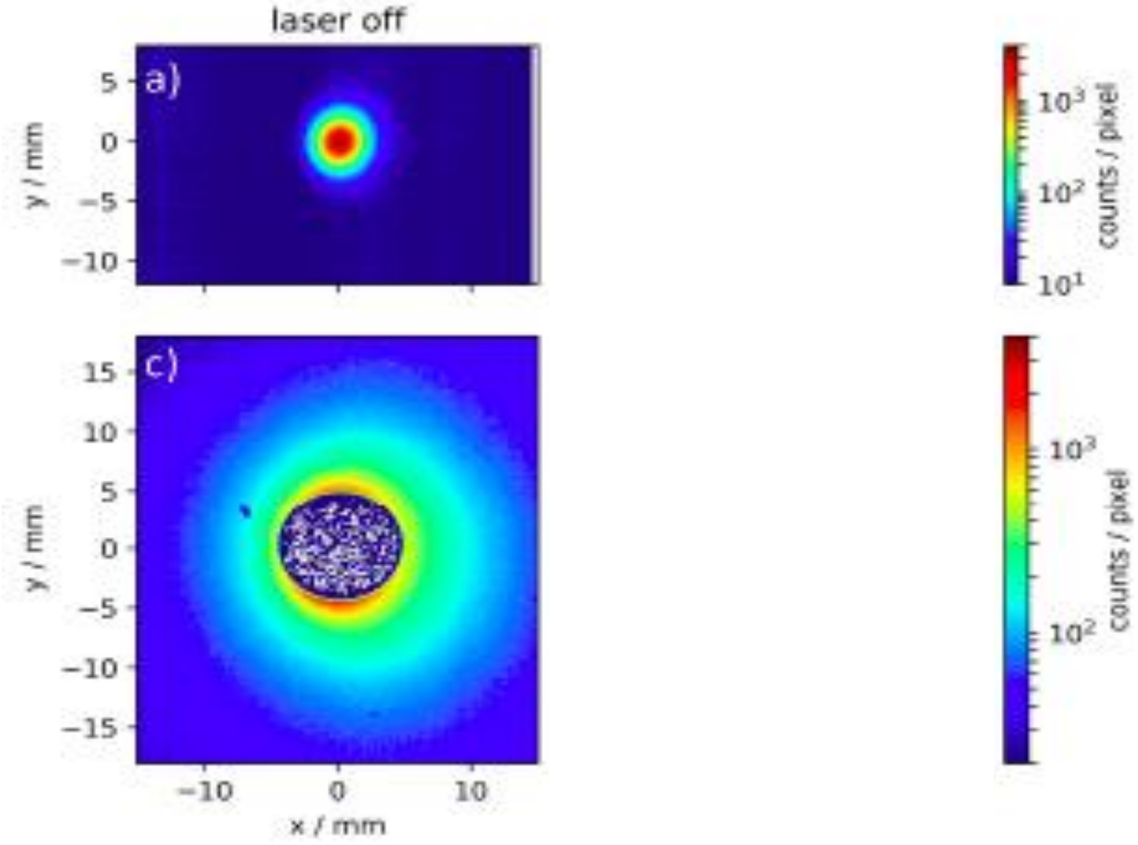
The long p^+ bunch (σ_z~12cm) self modulates with period λ_{pe}~1.2mm,
→ 100λ_{pe} per σ_z

Seeded Self-Modulation Diagnostics I



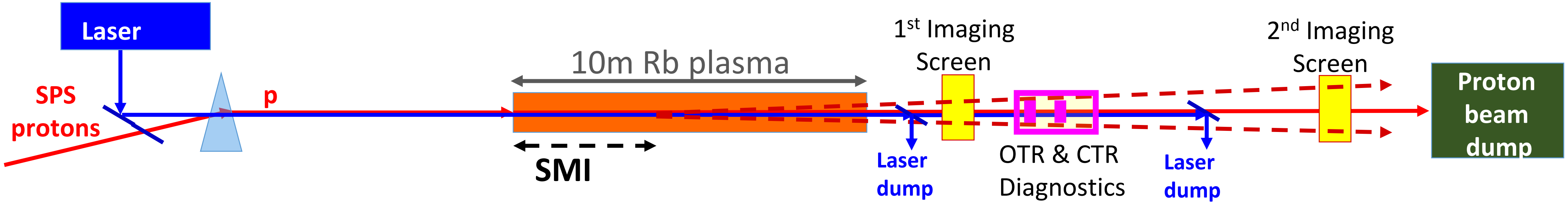
Indirect SSM Measurement: **Image protons that got defocused by the strong plasma wakefields.**

M. Turner, CERN



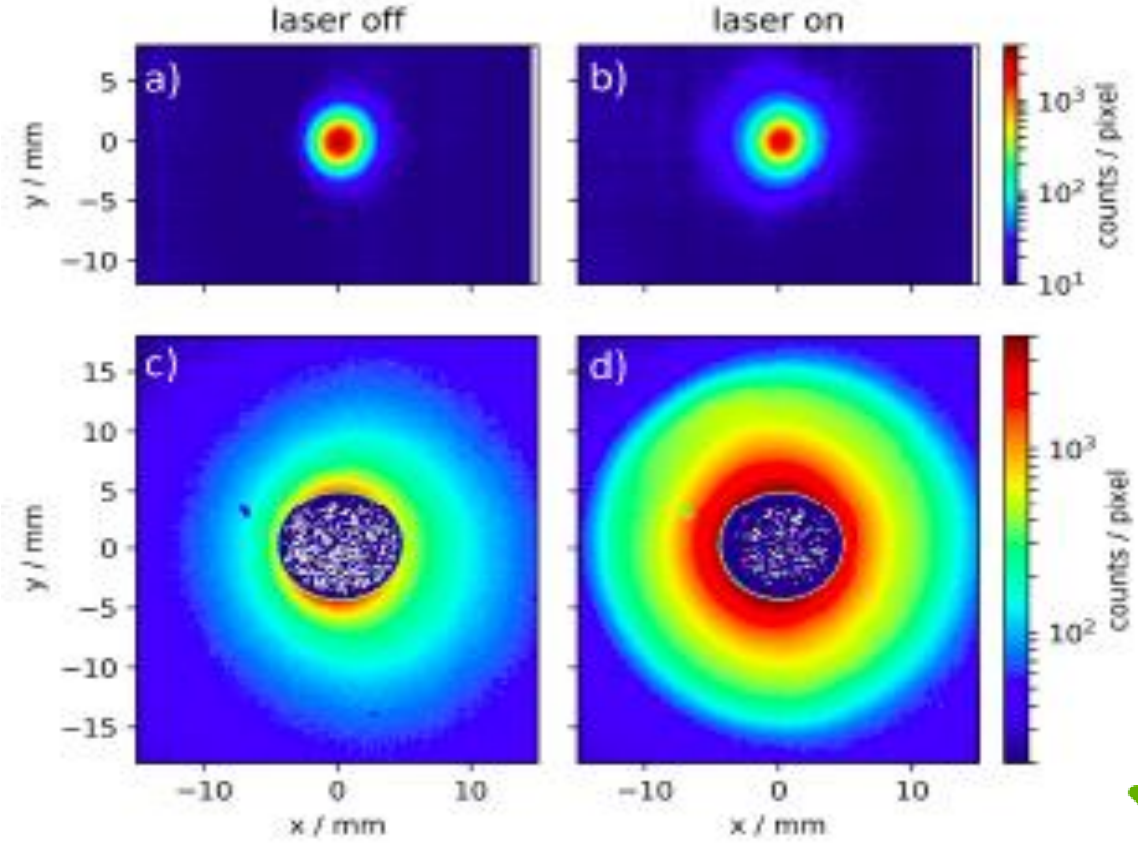
Two imaging stations (IS) to measure the **radial proton beam distribution** 2 and 10 m downstream the end of the plasma.
→ Growth of tails governed by transverse fields in the plasma.

Indirect Seeded Self-Modulation Results



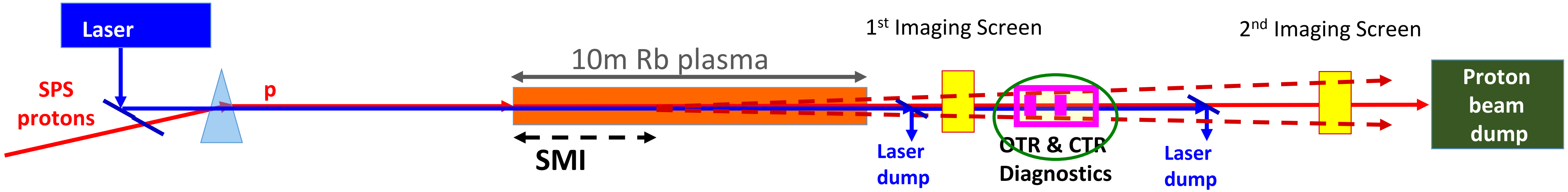
Indirect SSM Measurement: **Image protons that got defocused by the strong plasma wakefields.**

- → p^+ defocused by the transverse wakefield (SMI) form a halo
- → p^+ focused form a tighter core
- → Estimate of the transverse wakefields amplitude ($\int W_{per} dr$)



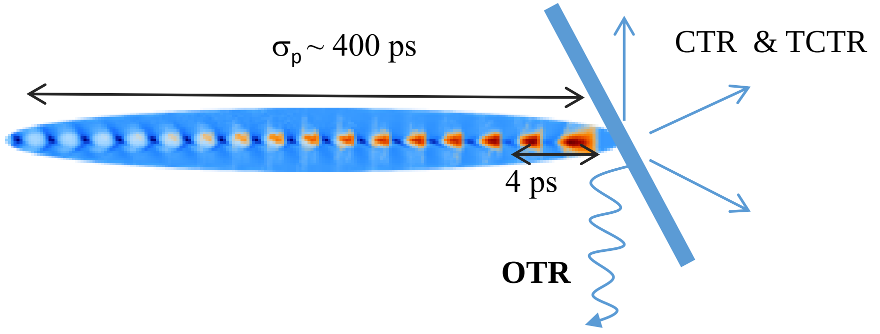
M. Turner, CERN

Seeded Self-Modulation Diagnostics II



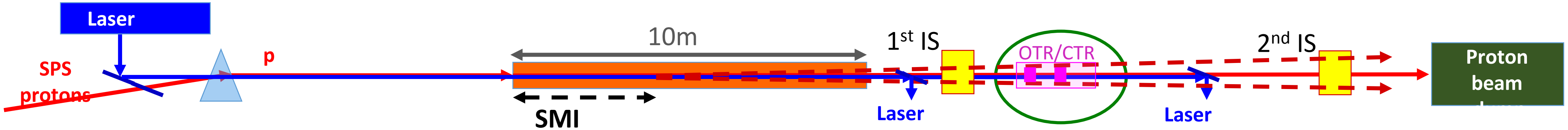
Direct SSM diagnostic: Measure frequency of modulation.

OTR: Optical Transition Radiation: Temporal intensity of the OTR carries information on bunch longitudinal structure.



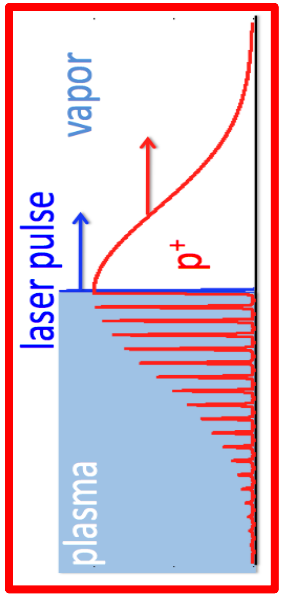
Streak Camera

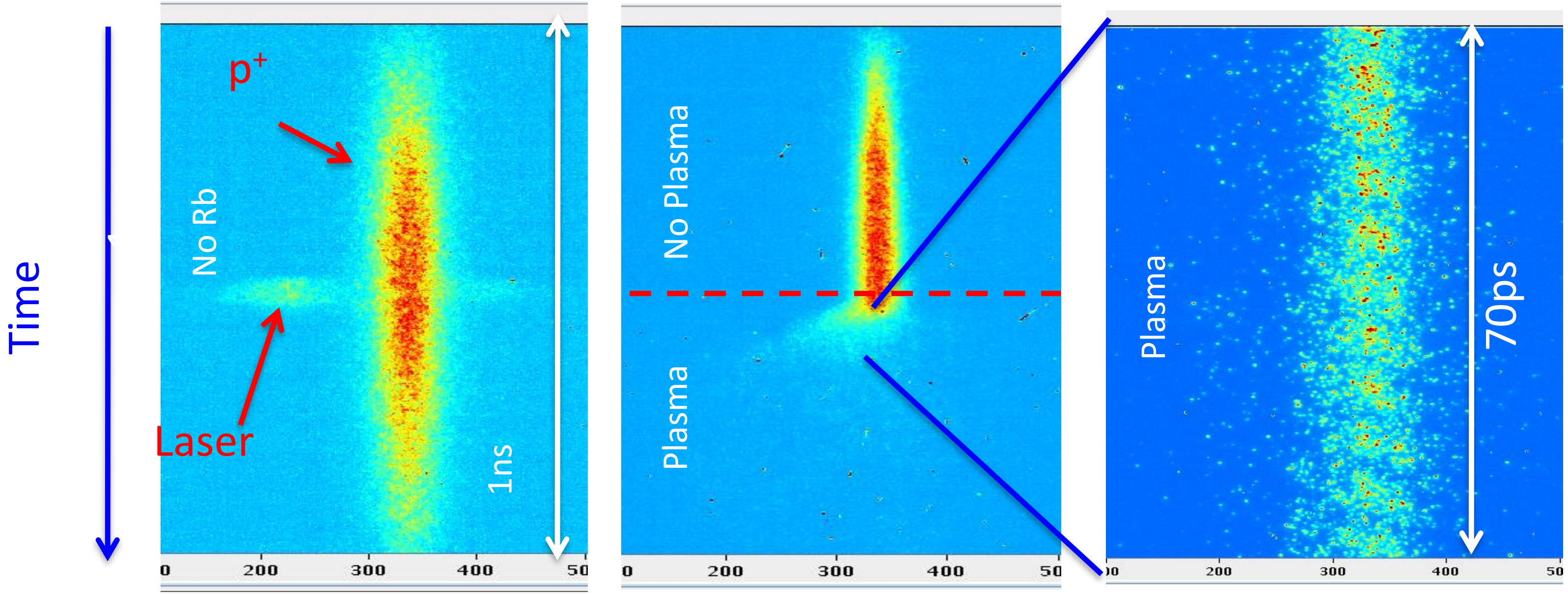
Direct Seeded Self-Modulation Results



K. Rieger, MPP

Streak camera Images





Preliminary!!!

$n_{Rb}=3.7\times10^{14}cm^{-3}$

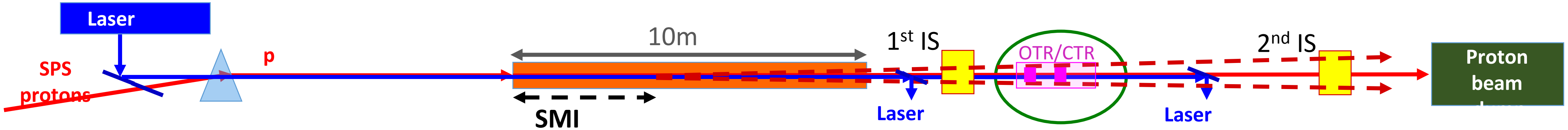
→ $\lambda_{Rb\text{-}plasma}$ = 1.8 mm

→ f_{mod}~164 GHz

$N_{protons}=3\times10^{11}$

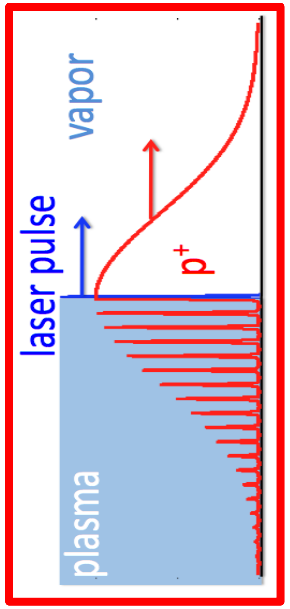
- → Timing at the ps scale
- → Effect starts at laser timing → SM seeding
- → Density modulation at the ps-scale visible

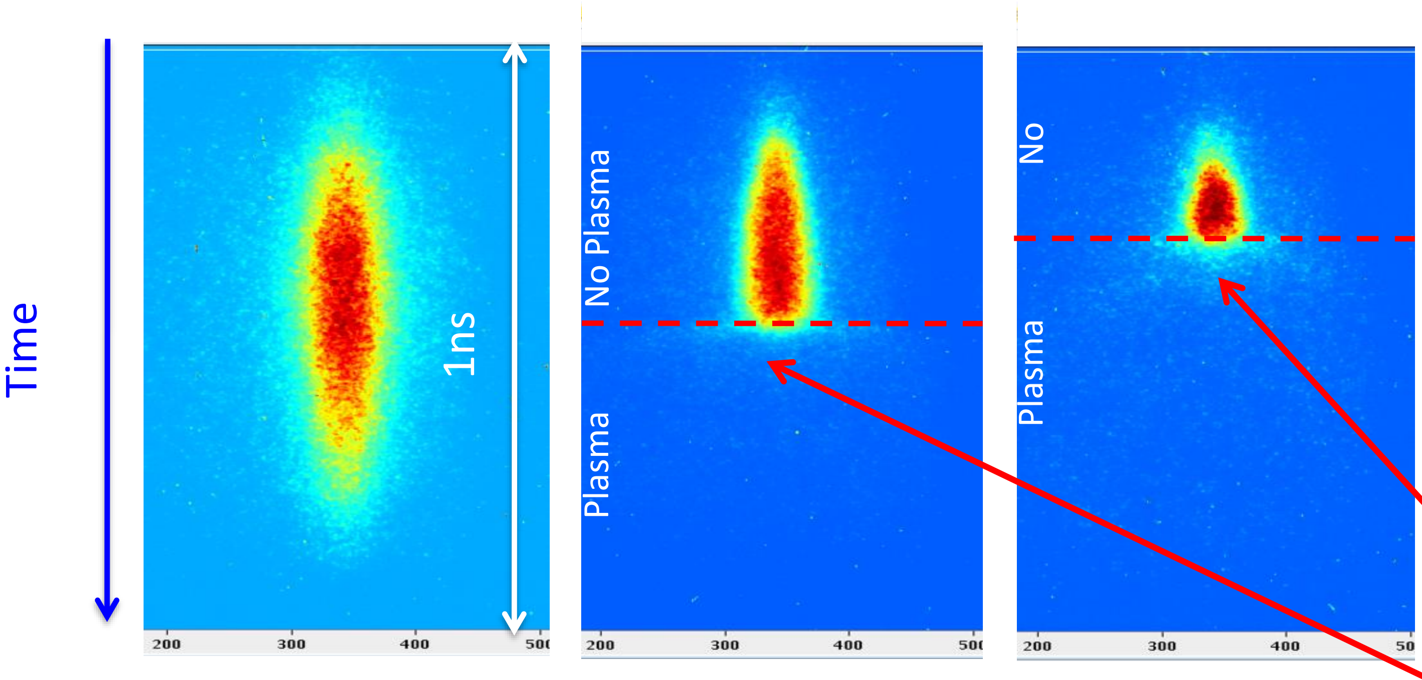
Direct Seeded Self-Modulation Results



K. Rieger, MPP

Streak camera Images



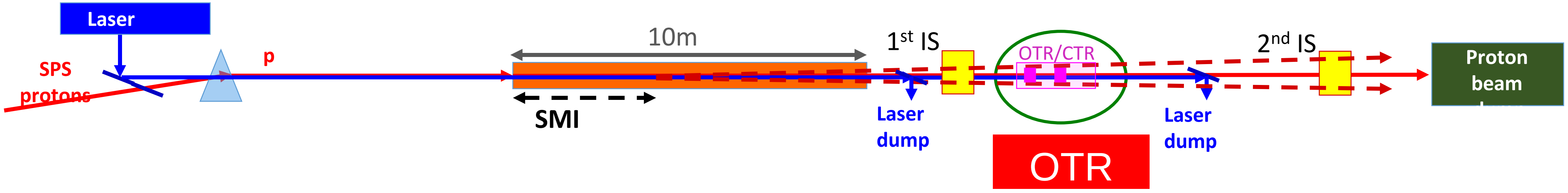


n_{Rb}=2.2x10^{14}cm^{-3}
N=3x10^{11}p$^+$

→ Various seeding position/times
→ Effect starts at laser timing → SM seeding

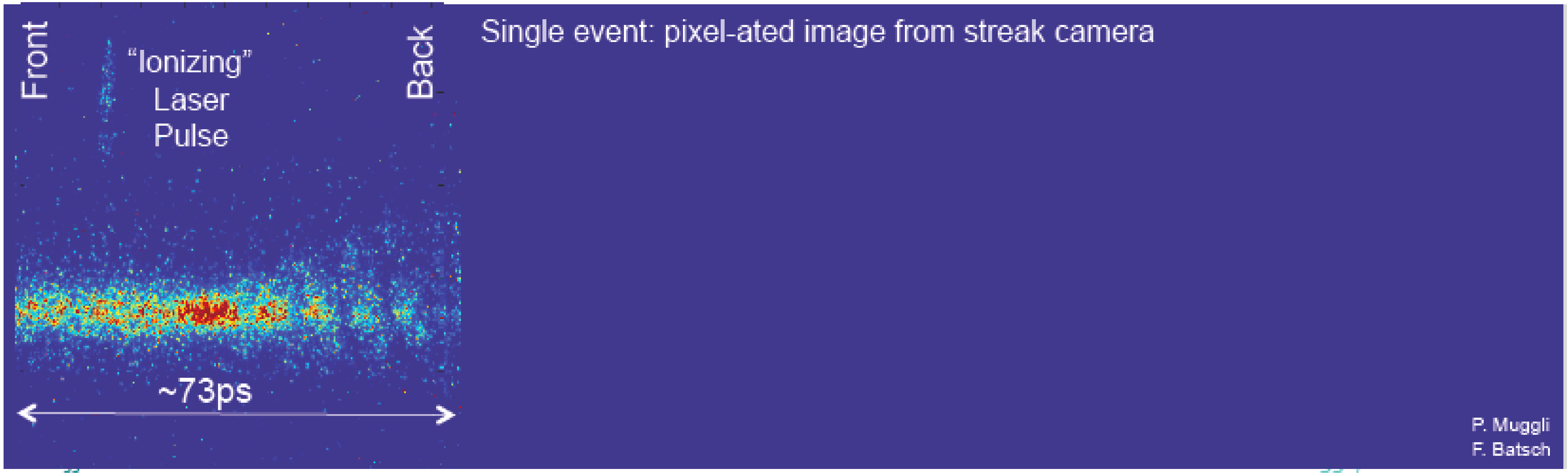
p$^+$ symmetrically defocused by SSM

Direct Seeded Self-Modulation Results



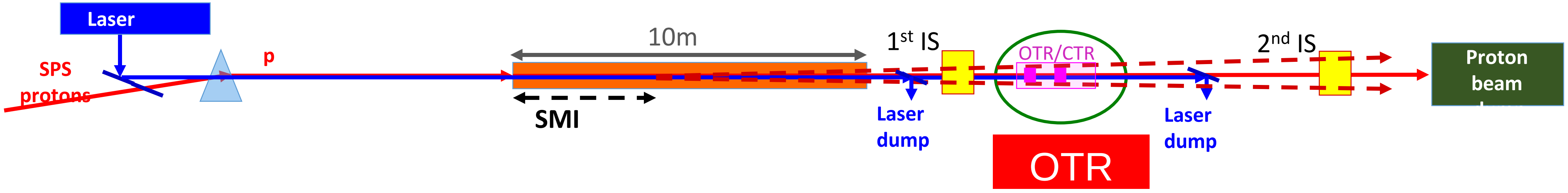
Streak camera Images

1 event



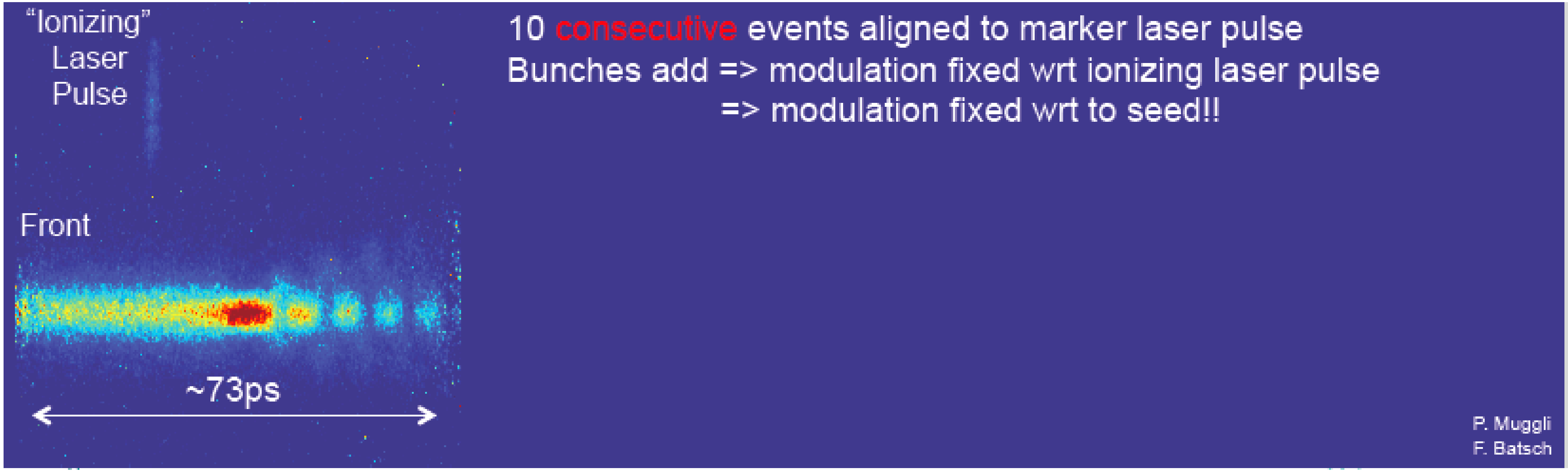
p-beam

Direct Seeded Self-Modulation Results



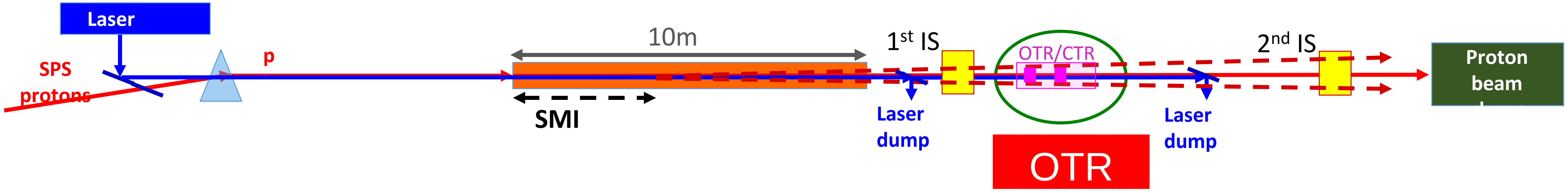
Streak camera Images

1 set, 10 events



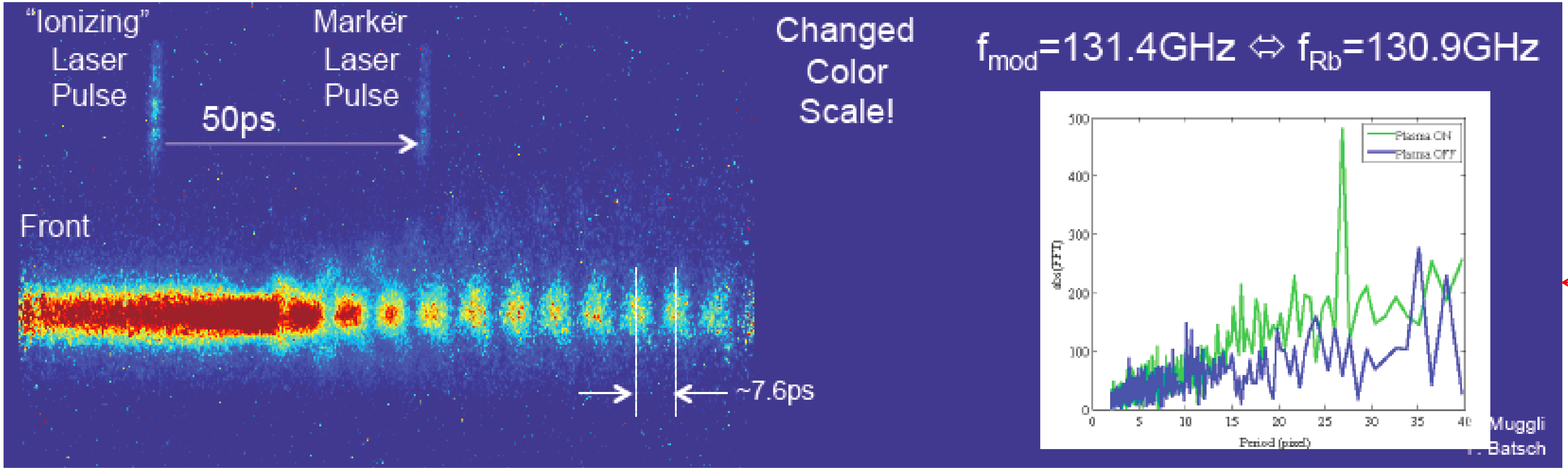
p-beam

Direct Seeded Self-Modulation Results



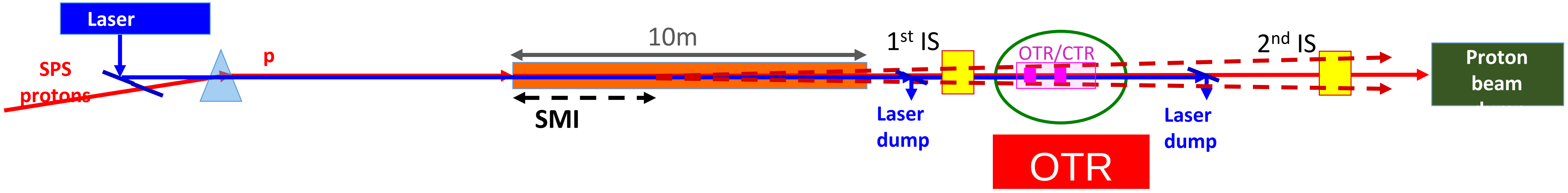
Streak camera Images

2 sets, 10 events each



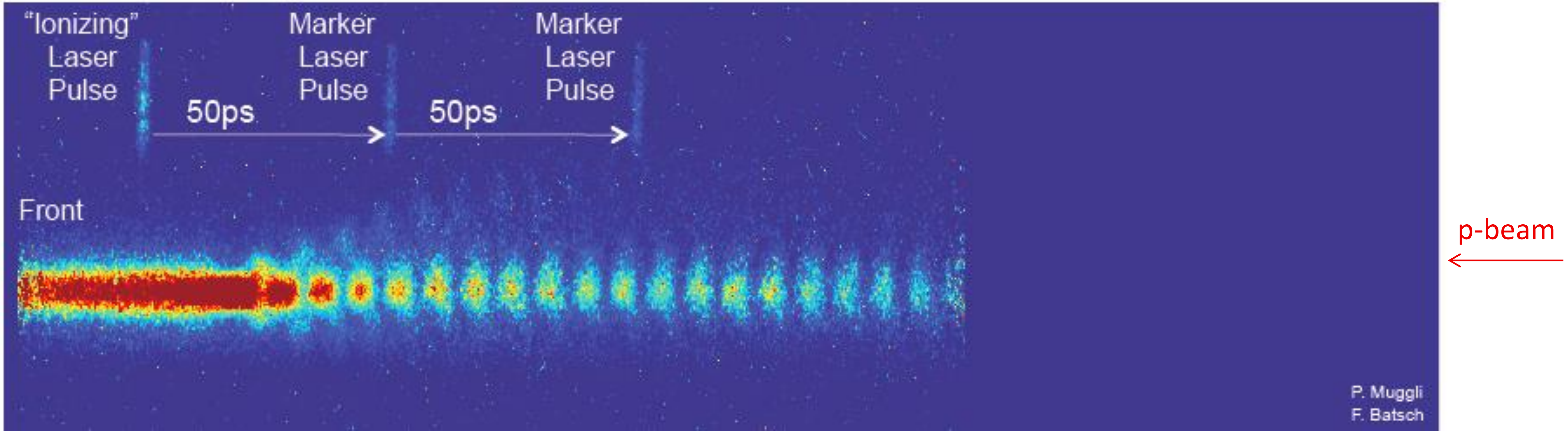
p-beam

Direct Seeded Self-Modulation Results

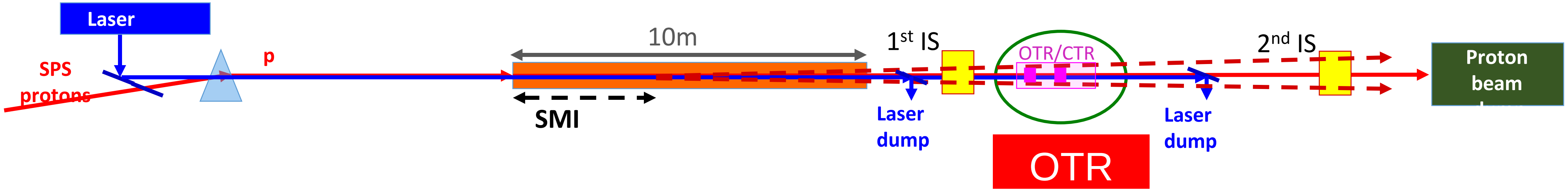


Streak camera Images

3 sets, 10 events each

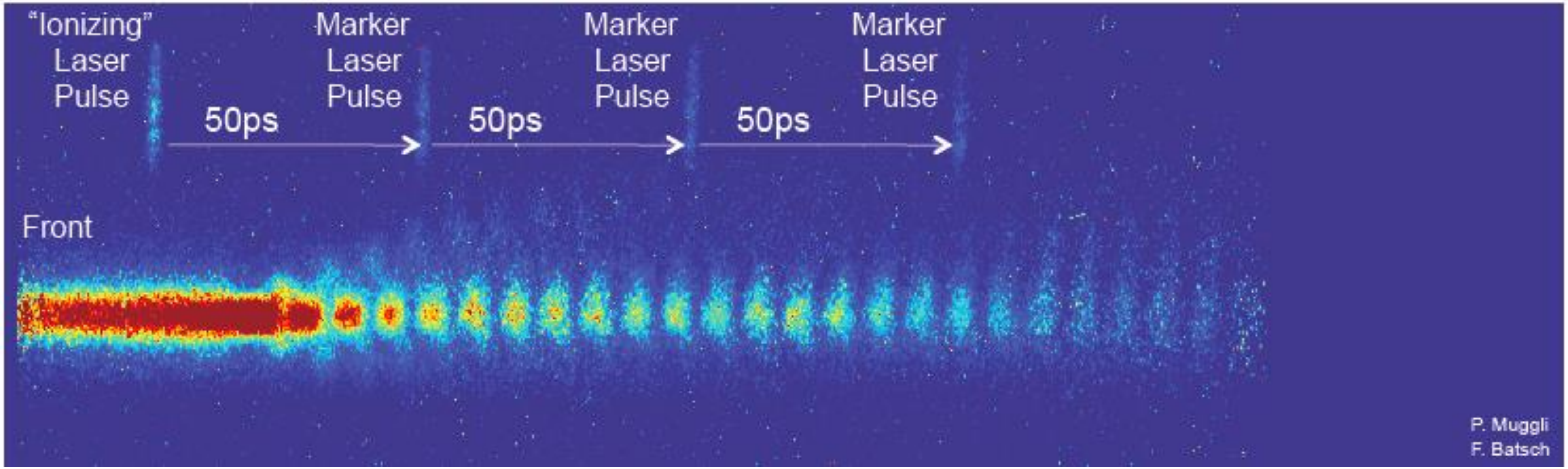


Direct Seeded Self-Modulation Results



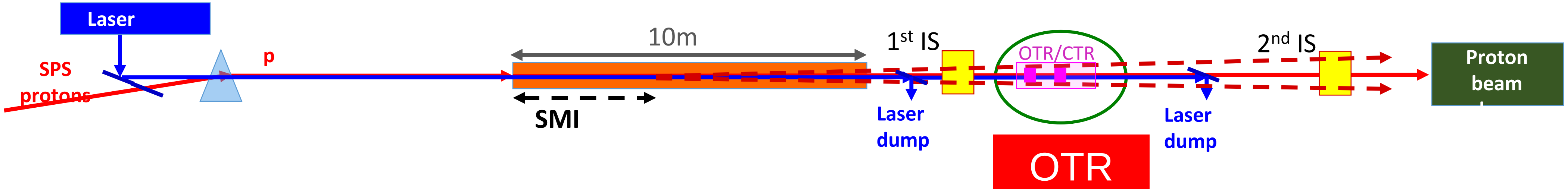
Streak camera Images

4 sets, 10 events each



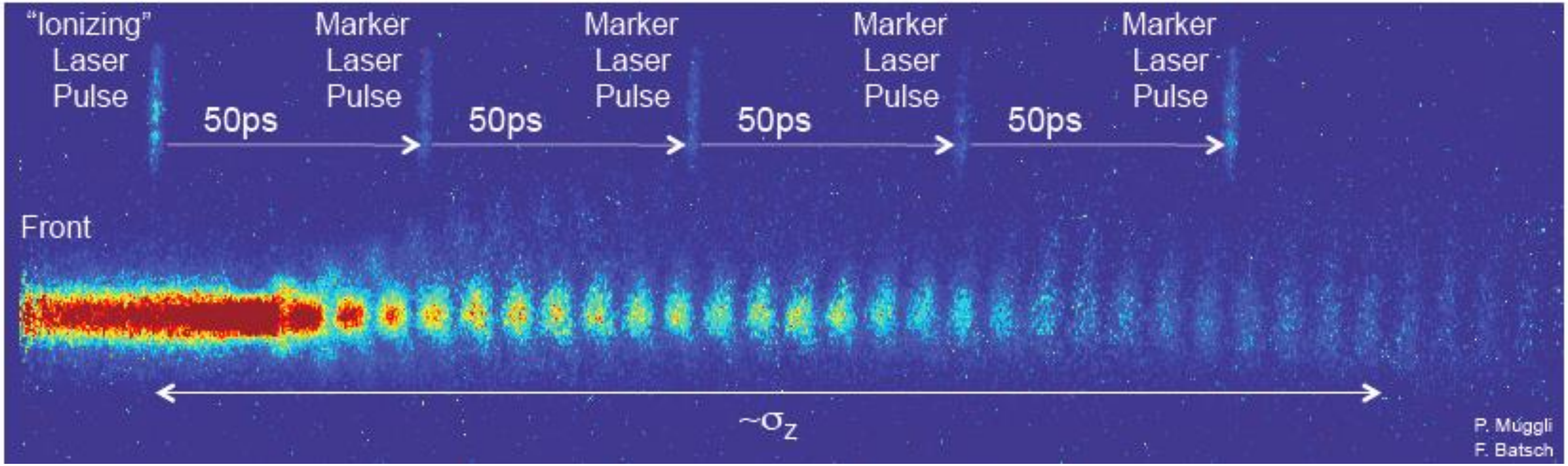
p-beam

Direct Seeded Self-Modulation Results



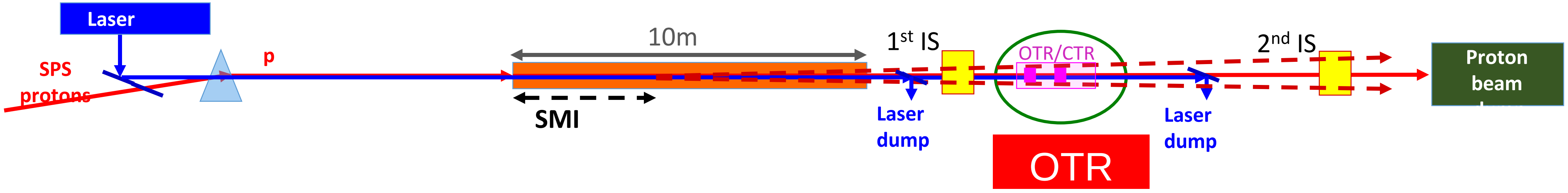
Streak camera Images

5 sets, 10 events each



p-beam

Direct Seeded Self-Modulation Results



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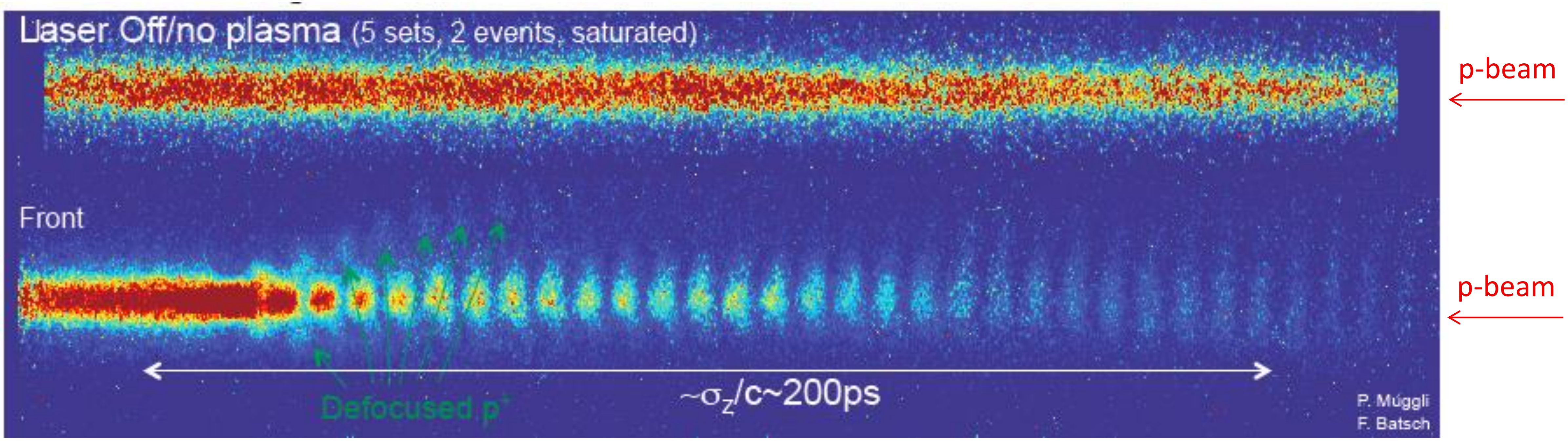
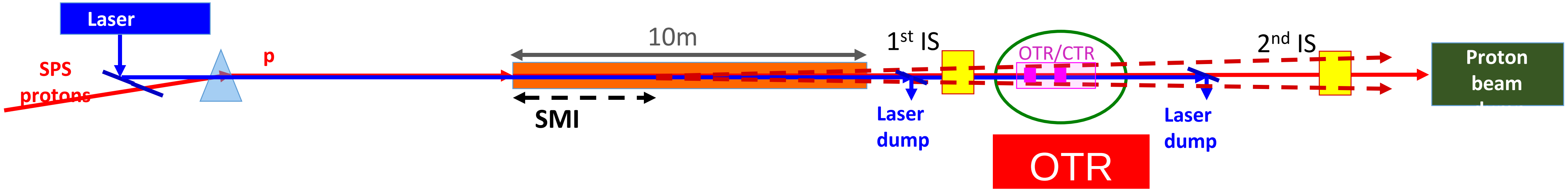
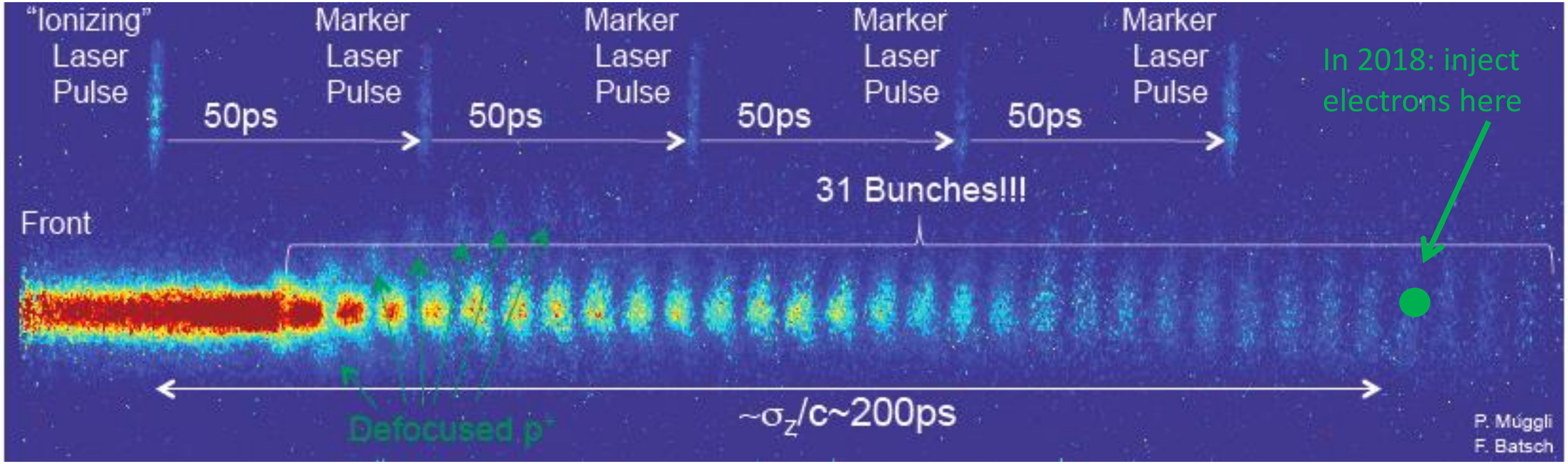


Direct Seeded Self-Modulation Results



Streak camera Images

5 sets, 10 events each



p-beam

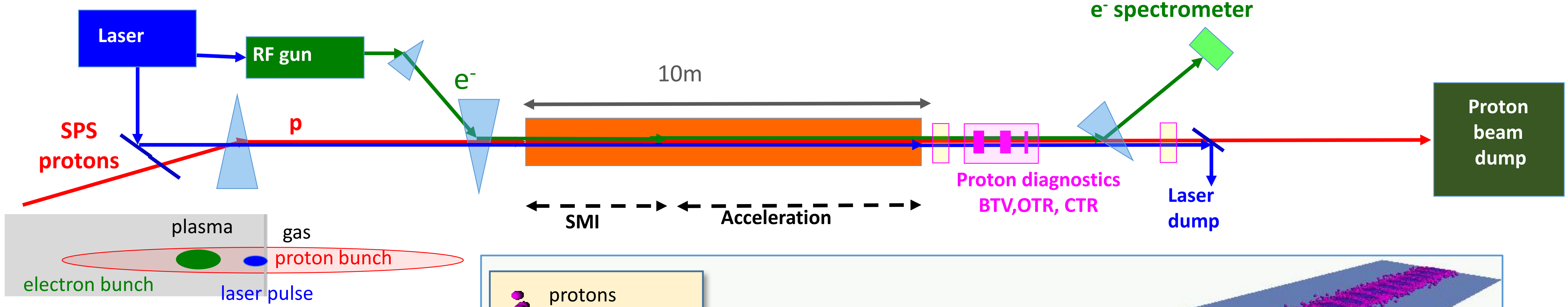
First milestone reached!

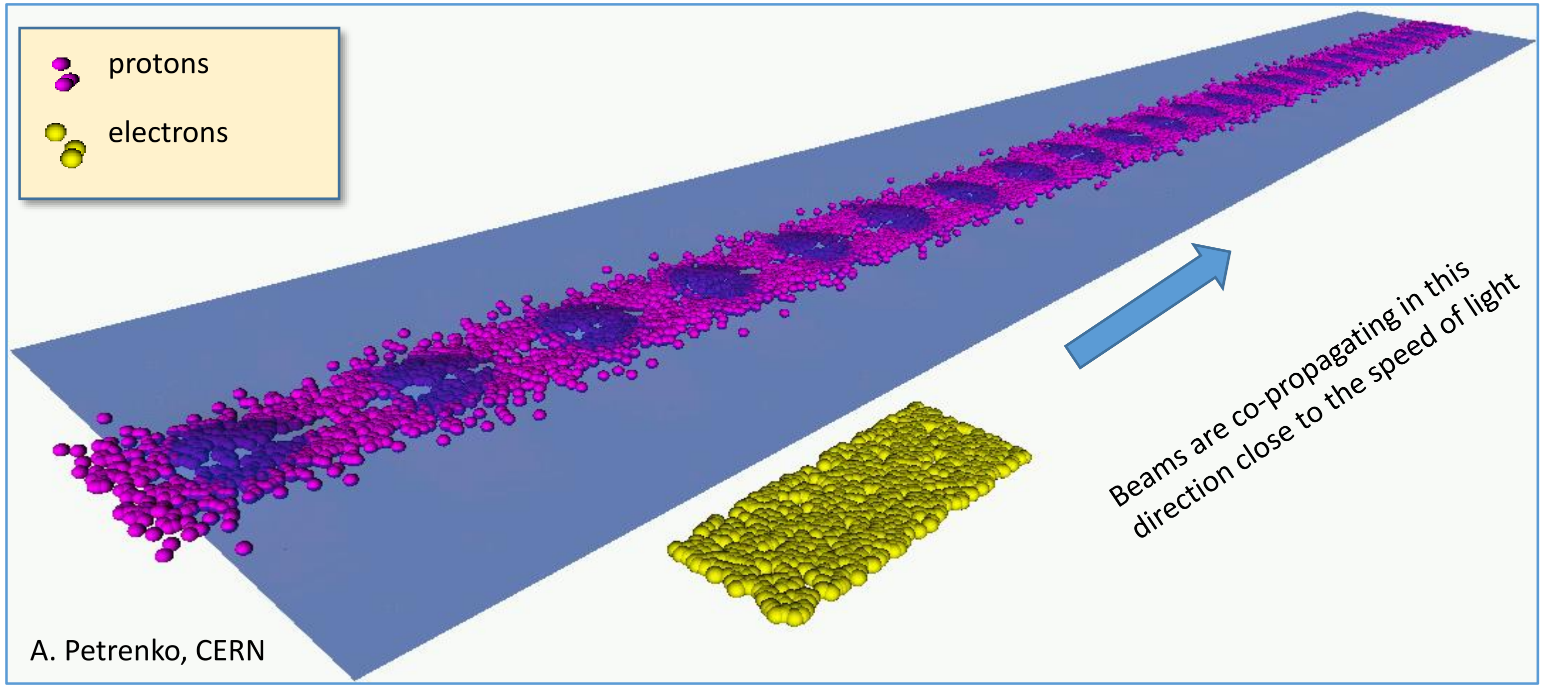
- Micro-bunches present over long time scale ~σ^{+}_{z}/c from seed point
- "Stitching" demonstrates reproducibility of the μ-bunch process against bunch parameters variation (N=2.5x10^{11}±10%, σ_{zt}=220±10ps, σ_r)
- Phase stability essential for e^- external injection: SSM not SMI!!! → Wakefields "amplifier"

AWAKE Experiment: Electron Acceleration

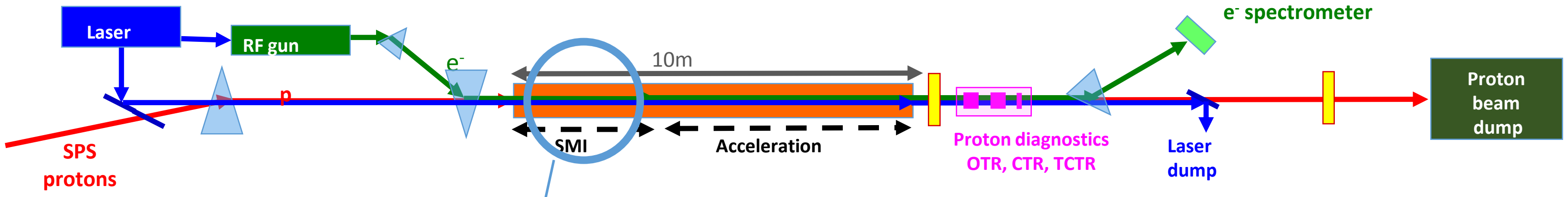
Phase 1: 2016/17: Understand **the physics of self-modulation instability** processes in plasma.

Phase 2: 2018: **2nd Milestone: Probe the accelerating wakefields** with externally injected electrons.

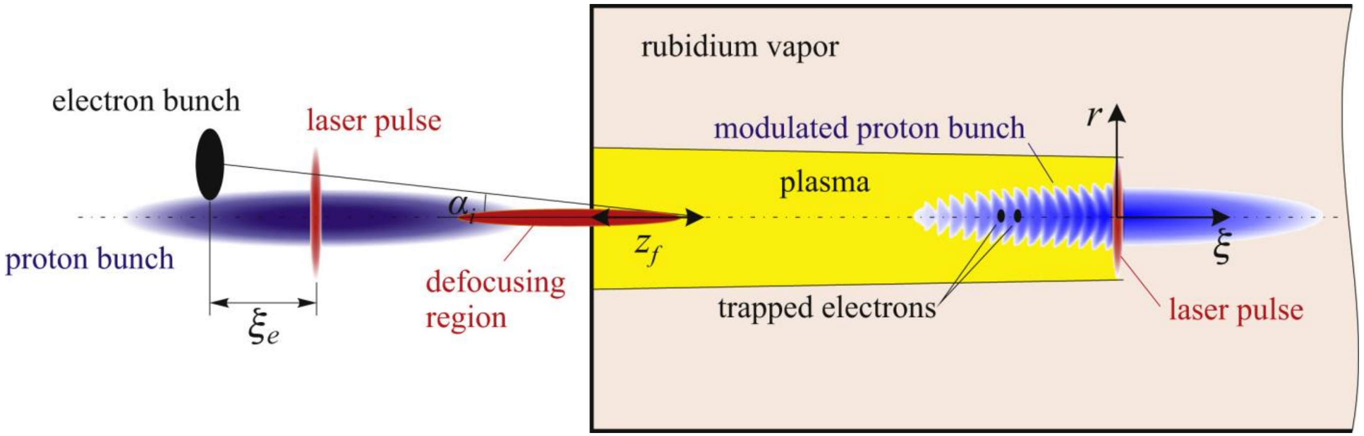


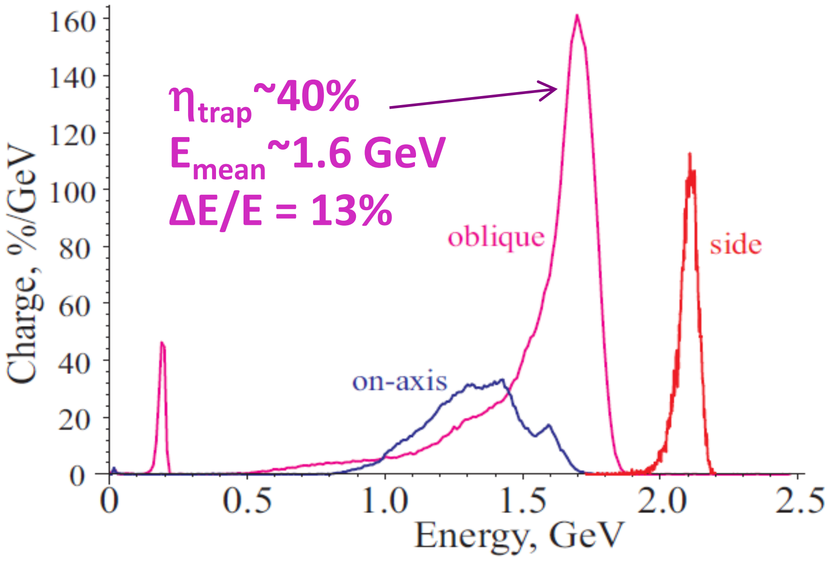


Electron Acceleration



Electron beam	Baseline
Momentum	16 MeV/c
Electrons/bunch (bunch charge)	1.25 E9
Bunch charge	0.2 nC
Bunch length	σ_z =4ps (1.2mm)
Bunch size at focus	$\sigma^*_{x,y}$ = 250 μm
Normalized emittance (r.m.s.)	2 mm mrad
Relative energy spread	$\Delta p/p$ = 0.5%

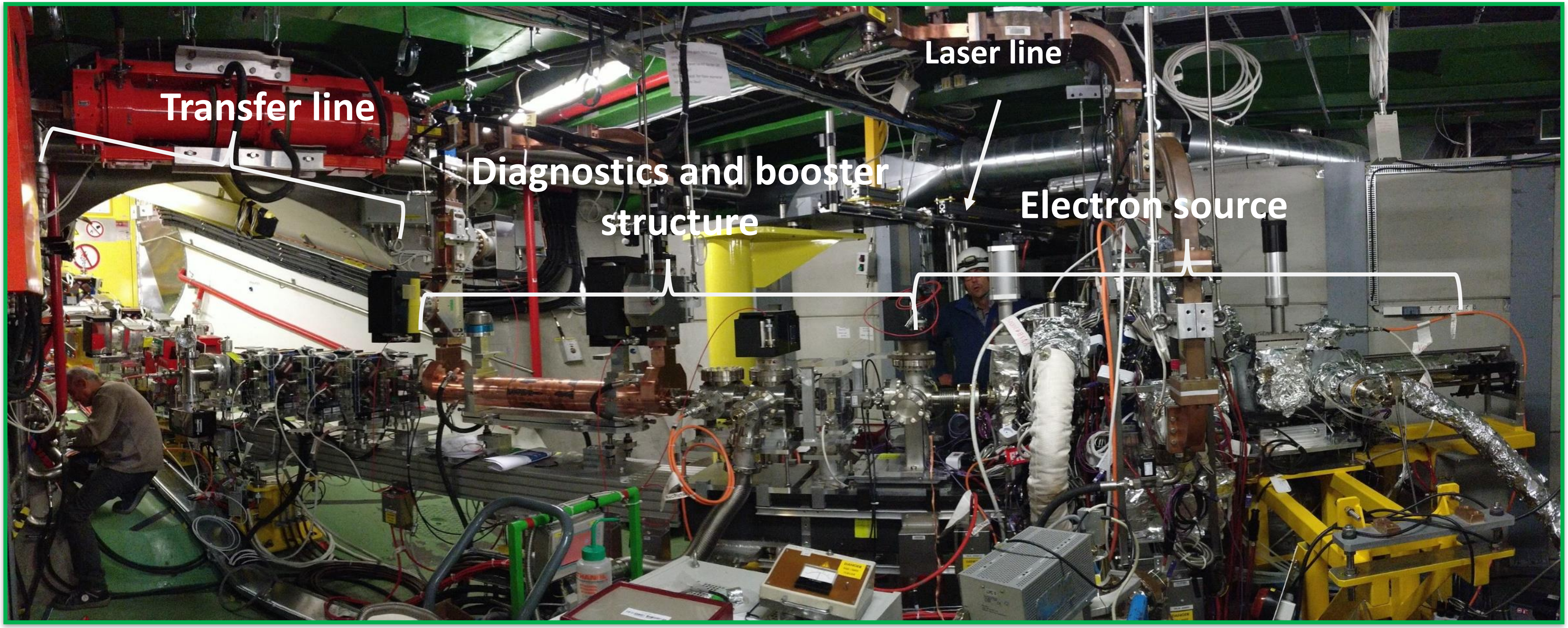




A. Caldwell et al., AWAKE Coll., Nucl. Instrum. A 829 (2016) 3

Externally inject electrons and accelerate e$^-$ to GeV energy with ~GeV/m gradient and finite ΔE/E

Electron Source



Installed in 2017 and first commissioning done

Electron Spectrometer System

Installed in 2017 and first commissioning done

AWAKE Program until First Beam in 2018

Commissioning of the electron source, beam line, electron spectrometer and test with beams of entire AWAKE facility (plasma cell, diagnostics, protons, electrons, laser) during the **last weeks of SPS in December 2017**

Useful data taking during end 2017 → allowed to prepare detailed plan for 2018 run.

→**Continue full commissioning and improvements of electron system.** Improvements that will be done until first beam in April 2018:

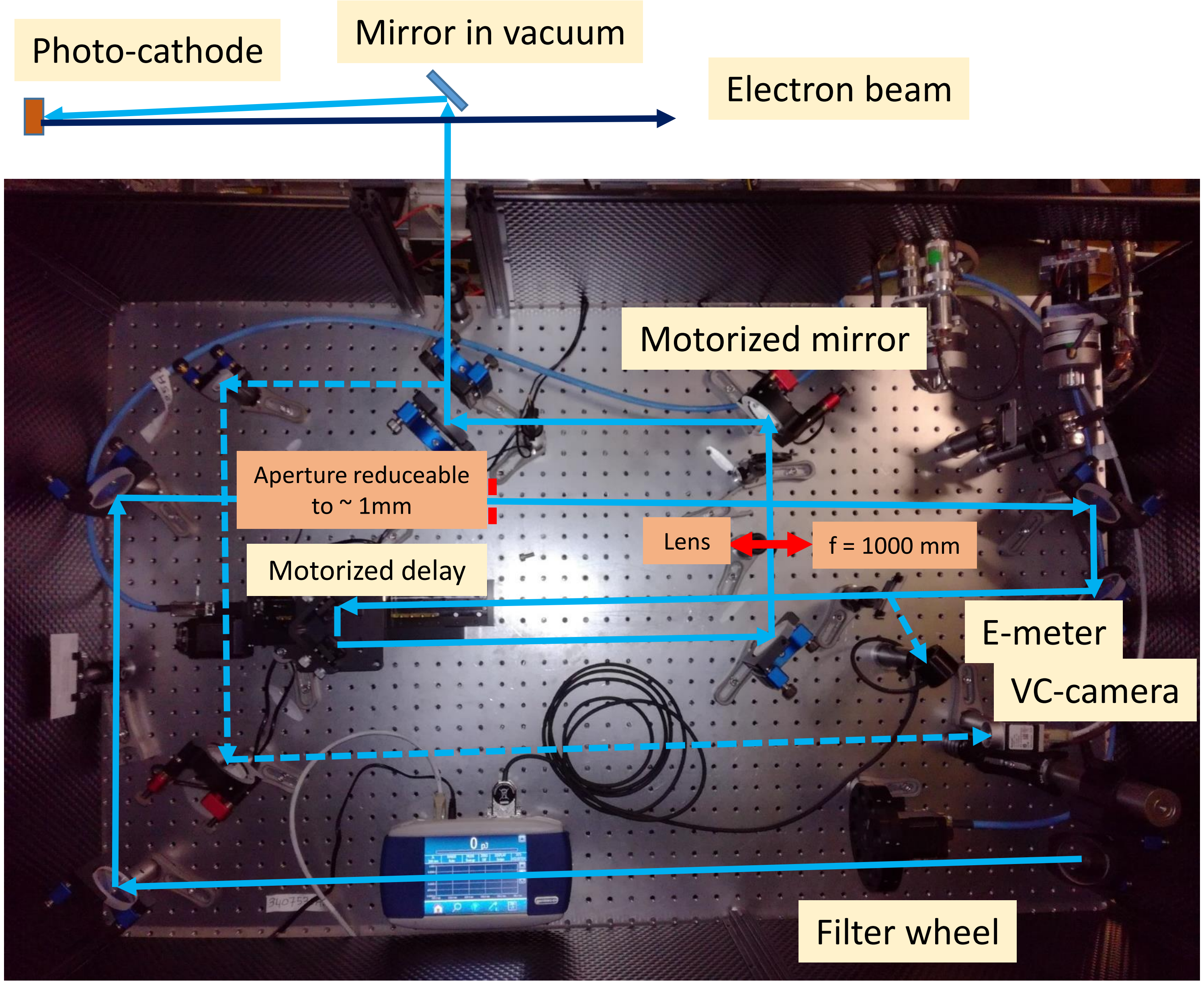
- **Significant jitter** in the laser spot caused a electron beam pointing jitter of several mm at the plasma
- **Electron beam emittance, energy spread**
- **Data acquisition and control systems** of e.g. spectrometer.
- **Additional electron diagnostics** upstream and around the plasma cell
- **Rearrangement of laser dump** and last BTV positions to measure beam modulation while operating the spectrometer.

➔ Intense program, all systems involved.

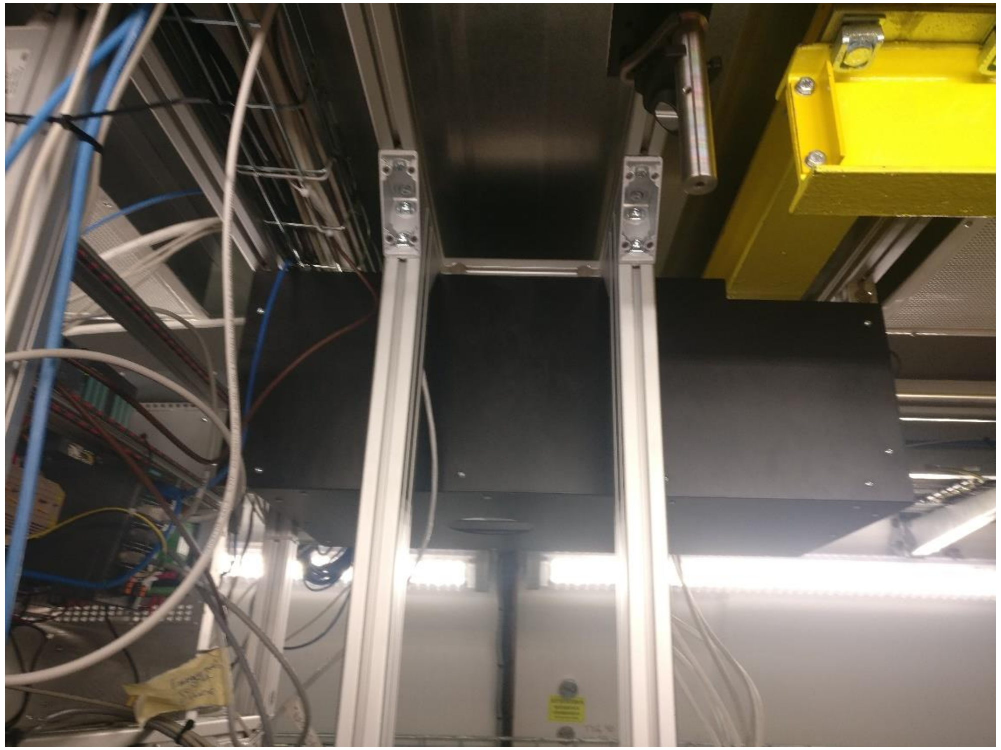
Laser

Delay Line and Virtual Cathode Setup with Aperture

Beam path from the 1st mirror on the table to the cathode = 5835mm



Laser Jitter Mitigation



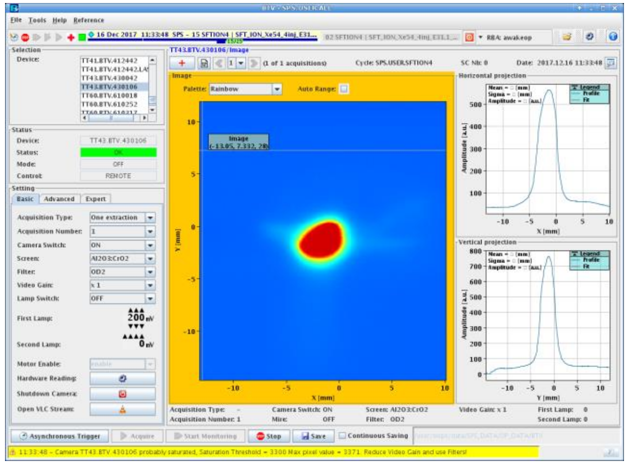
- Mirror platform - has been stabilized
- Add aperture

Electron Source

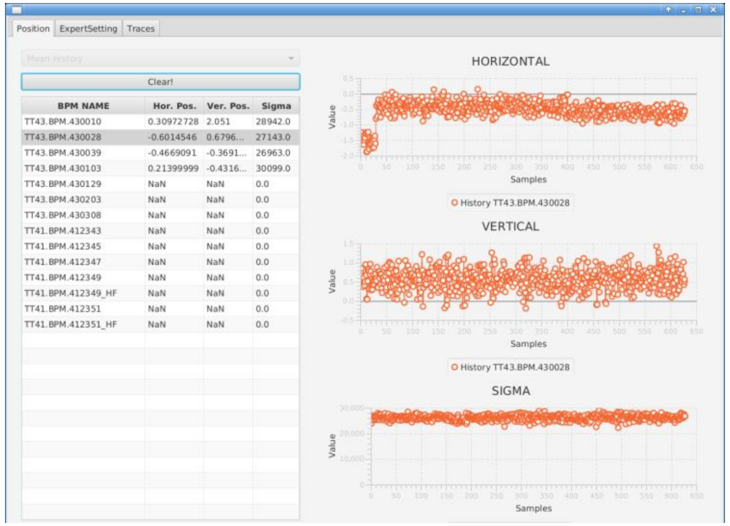
Status December 2017:

- Electron source fully installed and controllable
- Beam produced, quite reliable for the first experiments
- High-Power RF works as expected
- Energy of 16 MeV → Could go to 20 MeV ?
- Initially > 1 nC of bunch charge, then worked between 400 and 200 pC
- Emittance: much higher values as expected
- Jitter: identify all source of jitter and reduce as much as possible
- Improve some remote control and DAQ of certain signals
- Prepare automated measurement tools to optimise injector

Beam spot after booster



Beam Jitter observation



Status today (after March/April commissioning)

- BPMs show that jitter is < 100 mum in the beginning of the line
- Emittance is around 15 mm mrad and reproducible
  - Measured with Chromox, but screens blur and afterglow → use OTR?
- Energy jitter is below 0.1%

Electron Line

December 2017

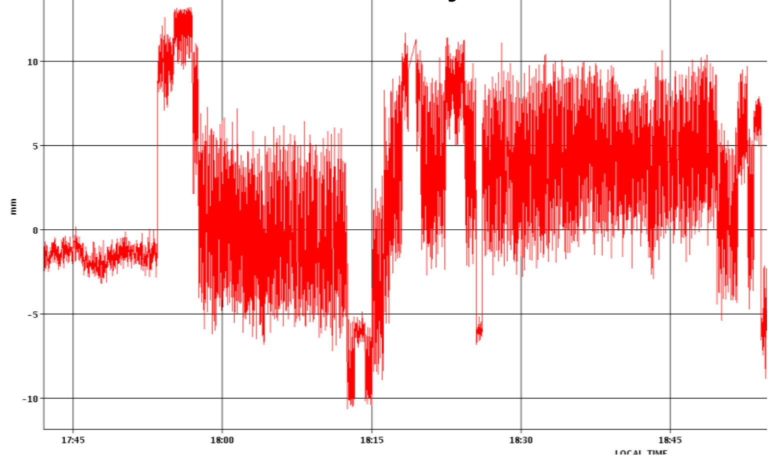
- Dominated by trajectory jitter (±5mm)❾no conclusive measurement!
- Preliminary observations and deductions:
  - Very likely mismatch between used and real Bρ ❾ affect beam size in particular towards the end of the line

Today:

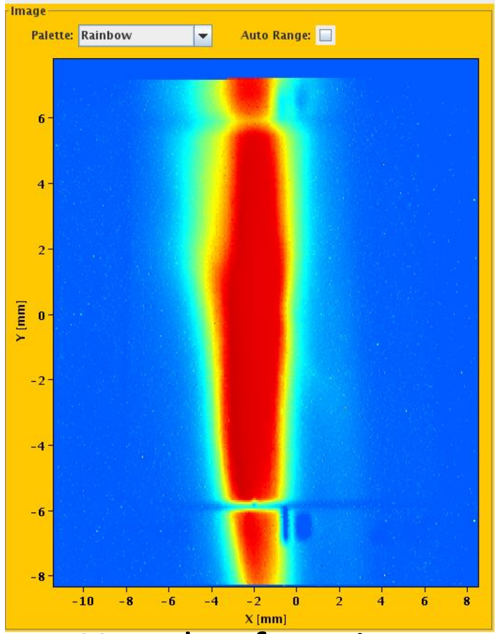
- Considerable progress! Beam is much better understood!
  - Edge effects need to be considered
  - Beam is focused at BTV screens upstream plasma

➔ **Further commissioning needed.**

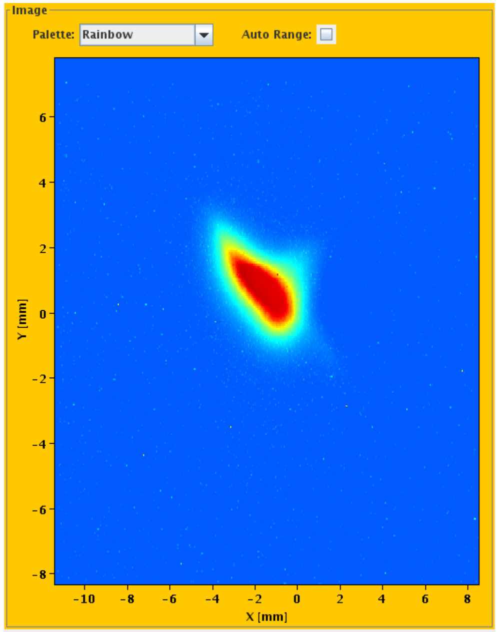
Beam jitter



BTV upstream the plasma cell



No edge focusing



Edge focusing

Additional Electron Diagnostics at Plasma Entrance I

Motivation & Layout

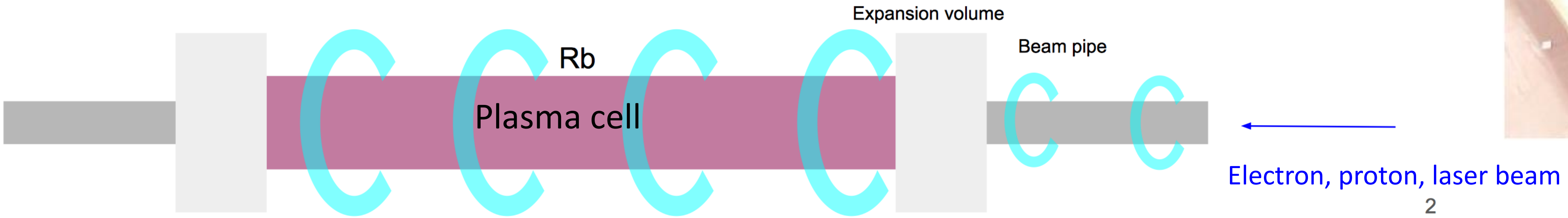
- ❑ Detect electrons that are lost along the beam-line and plasma and locate them during the experiment.

How it works:

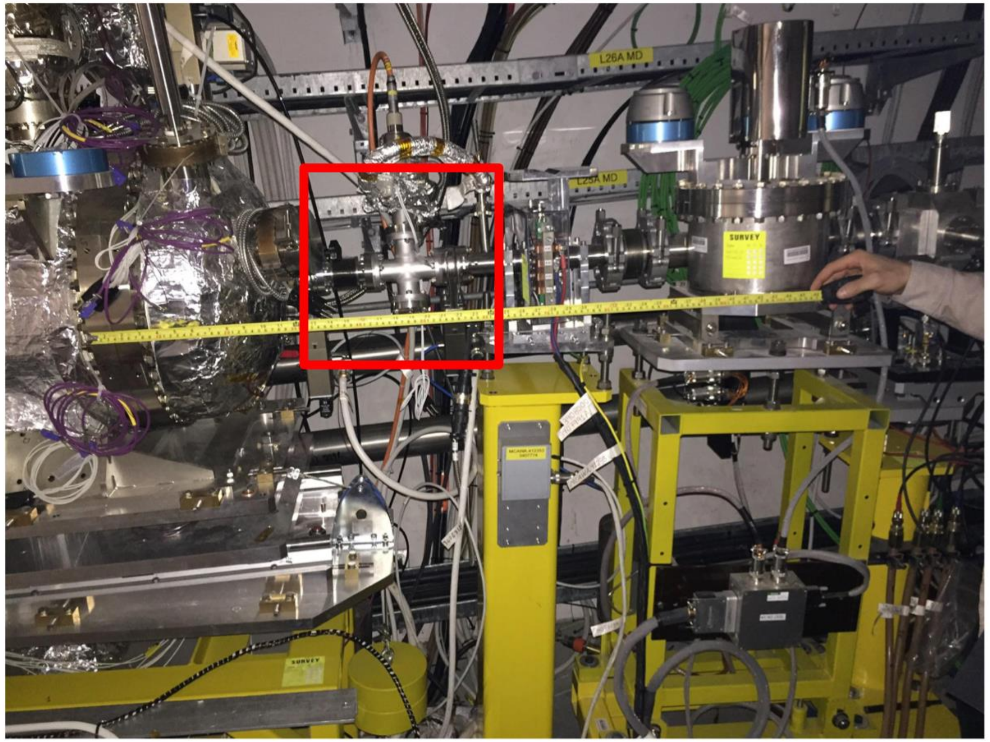
- ❑ Electrons interact with beam-pipe (and surrounding materials) and produce X-rays
- ❑ X-rays deposit energy in the fiber
- ❑ Fibers produce visible photons and transport them to a photomultiplier ⇒ Signal
- ❑ Each Fiber either gives a signal or not, Where and how many fibers to put?

Strategy: Have sth ready for the April measurement campaign, similar things (some of them far more complicated) have been installed at CERN...

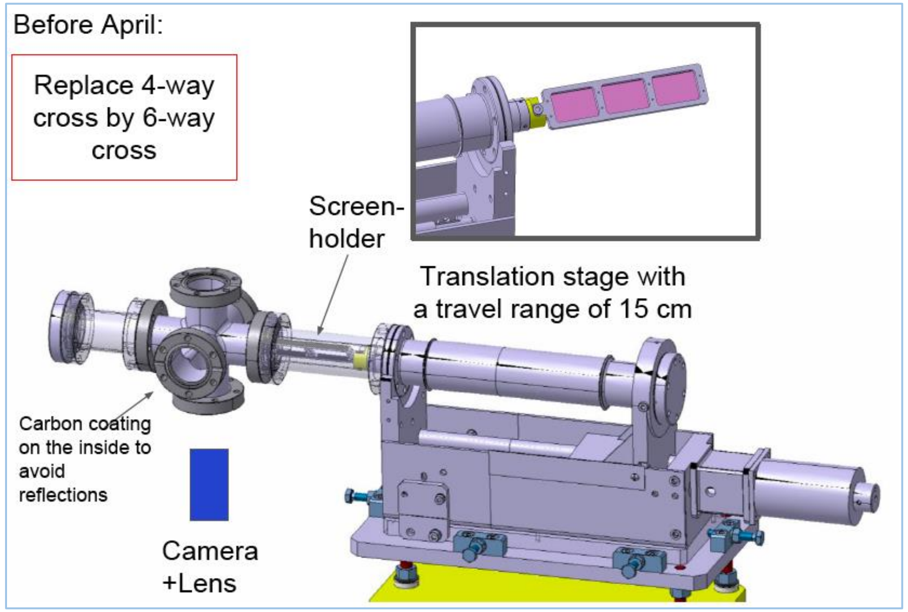
1) Scintillator paddles



Additional Electron Diagnostics at Plasma Entrance II

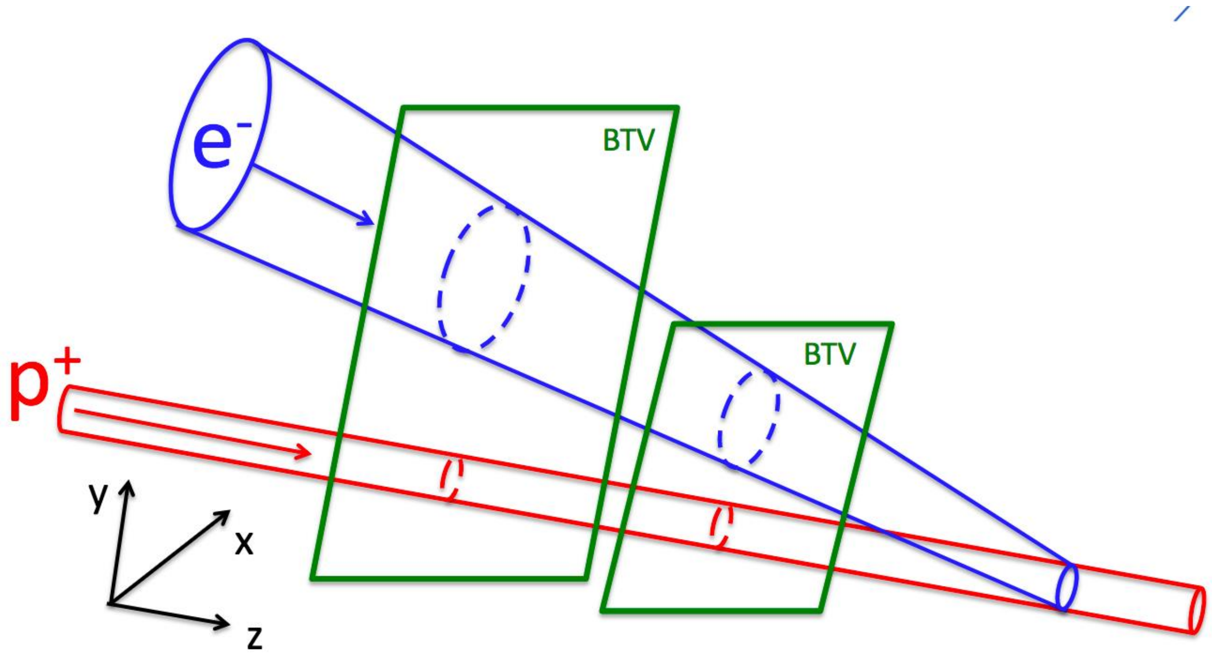


- **Idea:** Install a screen as close as possible to the entrance of the vapor cell.
  - Advantage:make modifications (i.e. changing screens) fast.
  - Try special screens to measure proton,electron, laser interaction
  - Measure proton electron interaction.
- Replace 4-way cross by 6-way cross and install an actuator and a viewport.
- Put screen-holder with different screens, 1D alignment



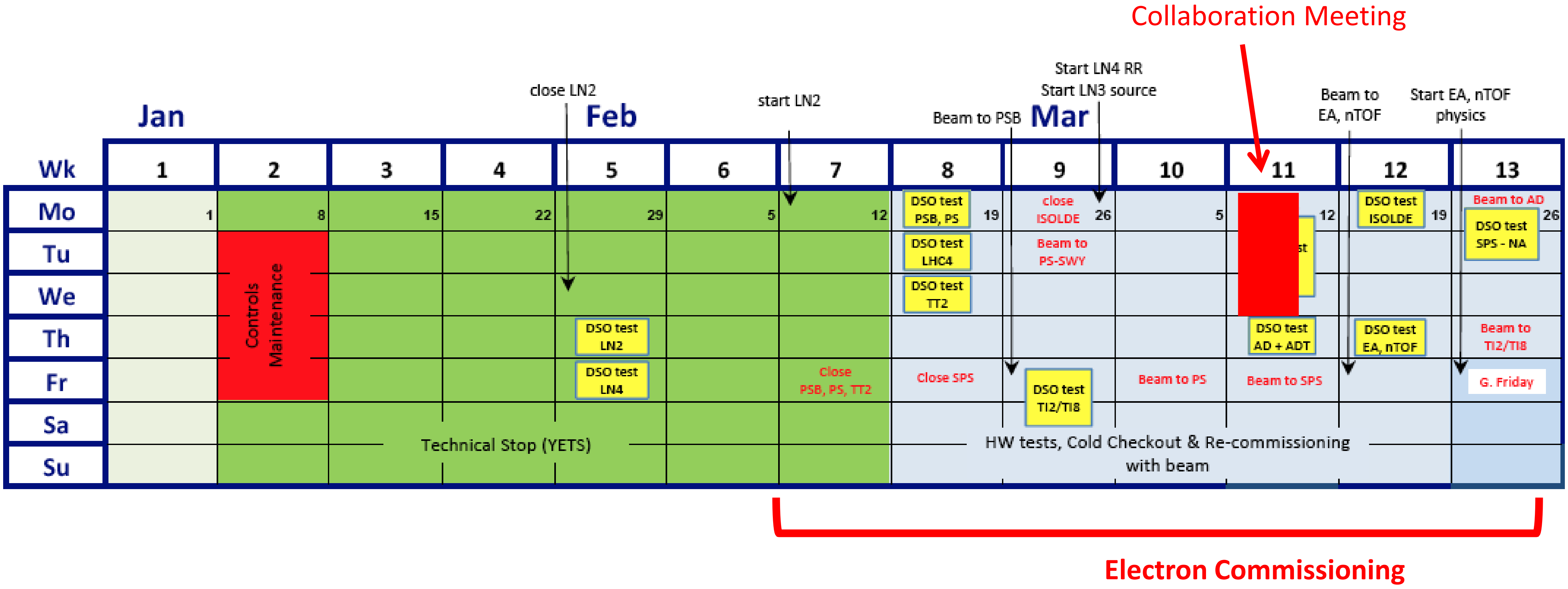
Challenges

We need all our tools fully under control in order to perform the 'real' experiment of electron acceleration.



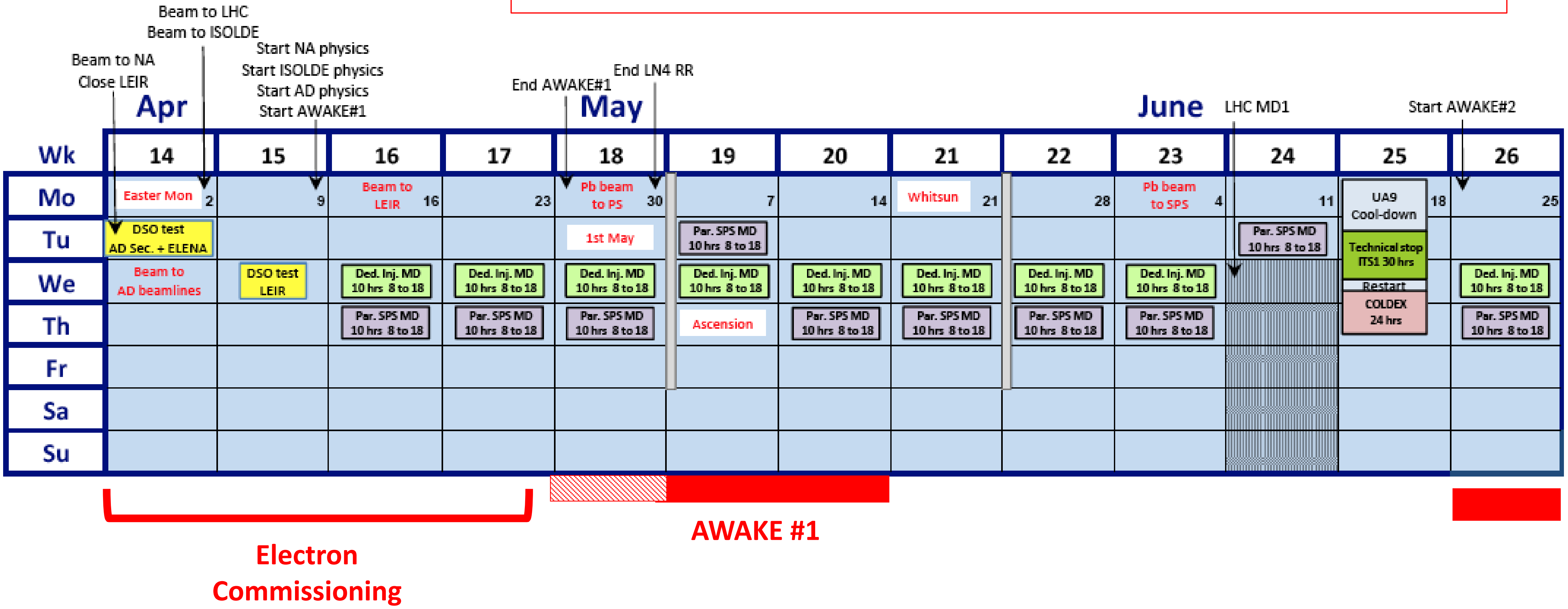
➔ Prerequisite for proton beam: have a fully commissioned electron beam!

2018 AWAKE Schedule



2018 AWAKE Schedule

➔ Prerequisite for proton beam to AWAKE: Electron beam is commissioned
➔ Shift start of AWAKE #1



2018 AWAKE Schedule

July — End AWAKE#2 — LHC MD2 — Aug — Start AWAKE#3 — Sep — LHC MD3 — End AWAKE#3

Wk	27	28	29	30	31	32	33	34	35	36	37	38	39
Mo	2	9	16	23	30	6	13	20	27	3	10	UA9 Cool-down 17	24
Tu										Par. SPS MD 10 hrs 8 to 18	Par. SPS MD 10 hrs 8 to 18	Technical stop ITS2 30 hrs	
We	Ded. Inj. MD 10 hrs 8 to 18	Ded. Inj. MD 10 hrs 8 to 18	Ded. Inj. MD 10 hrs 8 to 18		Ded. Inj. MD 10 hrs 8 to 18	Ded. Inj. MD 10 hrs 8 to 18	Ded. Inj. MD 10 hrs 8 to 18	Ded. Inj. MD 10 hrs 8 to 18	Ded. Inj. MD 10 hrs 8 to 18	Ded. Inj. MD 10 hrs 8 to 18		Restart	Ded. Inj. MD 10 hrs 8 to 18
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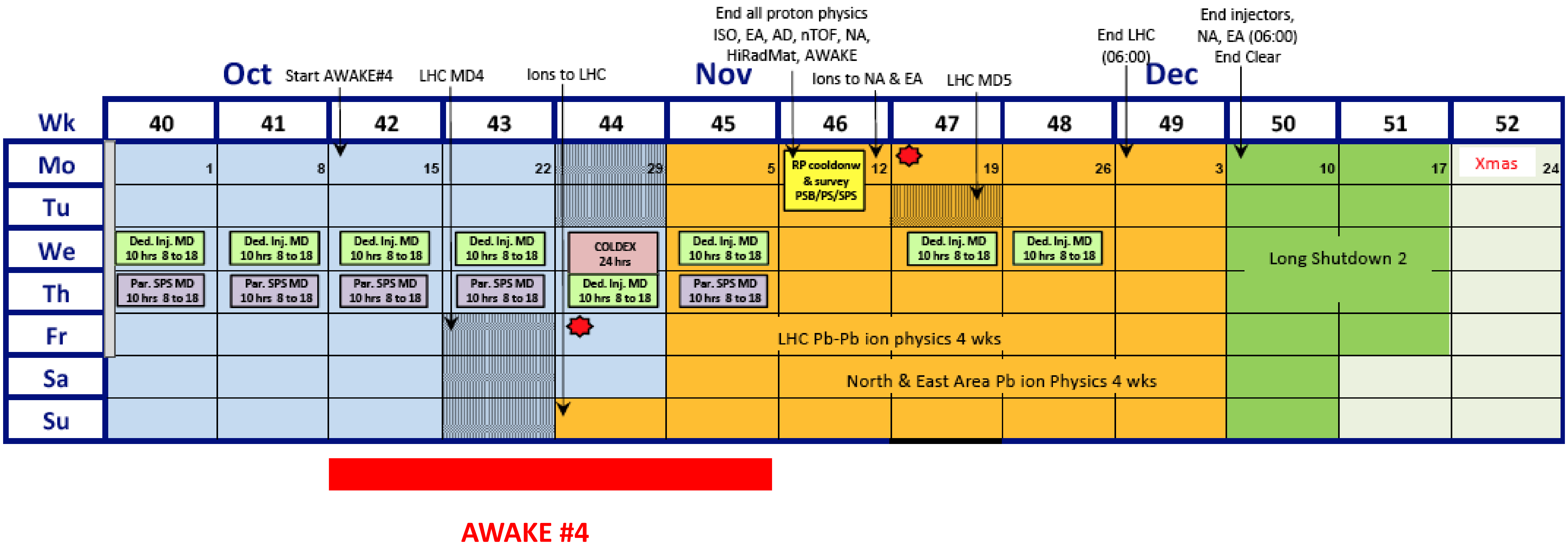
Sa													
Su													

AWAKE #2

AWAKE #3

2018 AWAKE Schedule



AWAKE Run 1 during LS2

Requirements for complementary measurements

- Laser, plasma, diagnostics and electron beam studies in current layout
- No changes in infrastructure required.
- Need functioning services such as **access system, cooling, ventilation, electricity** etc.

Tests during LS2 for Run1:

- Laser optimization on electron source
- Test of different cathodes
- Electron source optimization
- High quality stable electron beam into plasma: → depends on 2018 run
- Consistency, stability, reliability studies

- Laser + Rb vapour source:
    - Plasma studies
    - Laser studies
    - Diagnostics

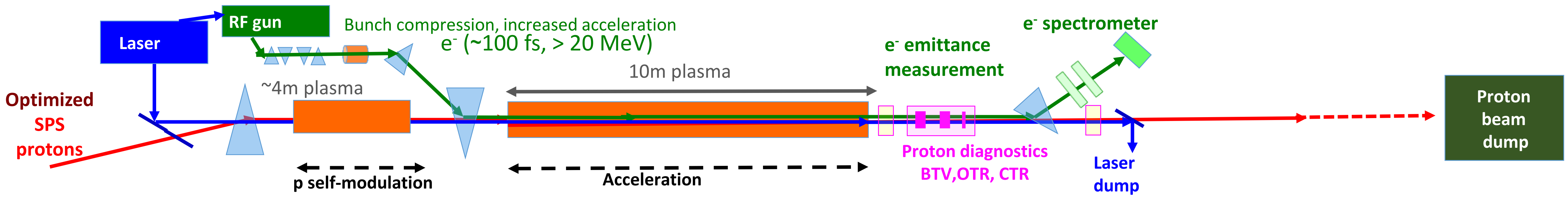
AWAKE Run 2 Studies during LS2

- Design report by 2018/2019 → details of Run 2 studies and preparation for future LS2C presentation
- Pending management approval:
  - Modify the area to install the Run 2 baseline layout.
  - No CNGS dismantling
  - Minor changes, minor personnel needs, more info end 2018 with design report.

AWAKE Run 2

Proposing Run 2, after LS2

- Accelerate an electron beam to 5 – 10 GeV in 10 – 20 m plasma cell.
- Demonstrate electron bunch emittance at < 10 mm mrad level
- Demonstrate scalability of the AWAKE concept



After AWAKE Run 2 and after LS3: get ready for first applications

- Use bunches from SPS with 3.5 E11 protons every ~5sec, electron beam of up to O (50GeV).

1. **fixed target test facility**: deep inelastic scattering, non-linear QED, **search for dark photons a la NA64.**
2. **collide** with LHC protons/ions

Summary

1st milestone reached in 2017: phase stable, reproducible Seeded Self-Modulation

2018 is a very important year for AWAKE:

2nd milestone: electron acceleration in plasma → high expectations!

→Now commissioning of electron beam system

→our tools for e-acceleration must be fully under control

→ first proton beam ~end April 2018

Proposing Run 2 of AWAKE (during Run 3 of LHC) for after LS2 → **depends on electron acceleration run 2018!**

→Run 2: Preserve electron beam quality, scalability of electron acceleration

Huge Effort of Many People! THANKS A LOT!!

EXTRAs

AWAKE Run 2

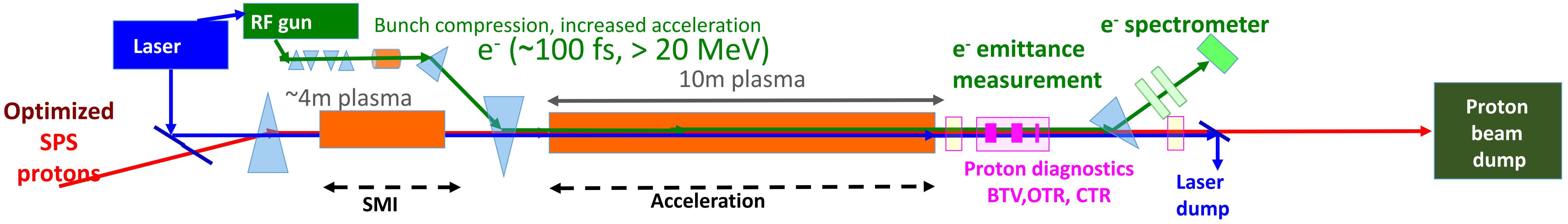
Proposing Run 2 for 2021 after CERN Long Shutdown 2

Goals:

- **Accelerate an electron beam to high energy**
- **Preserve electron beam quality** as well as possible
- **Demonstrate scalability** of the AWAKE concept

Preliminary Run 2 electron beam parameters

Parameter	Value
Acc. gradient	>0.5 GV/m
Energy gain	10 GeV
Injection energy	$\gtrsim$ 50 MeV
Bunch length, rms	40–60 μm (120–180 fs)
Peak current	200–400 A
Bunch charge	67–200 pC
Final energy spread, rms	few %
Final emittance	$\lesssim$ 10 μm

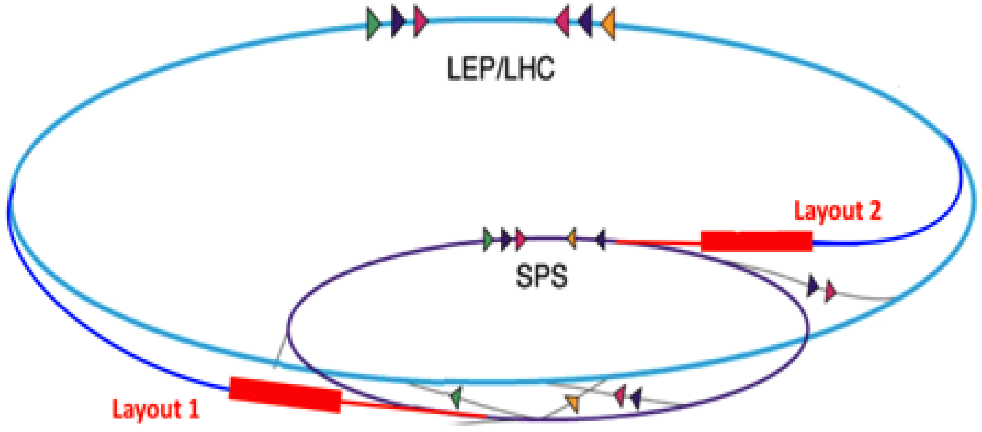


E. Adli (AWAKE Collaboration), IPAC 2016 proceedings, p.2557 (WEPMY008)

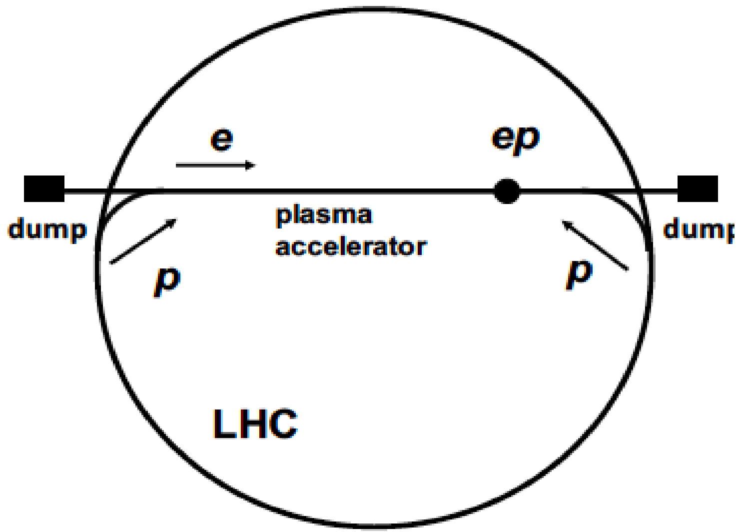
Application of Proton Driven Wakefield Acceleration Technology

- **Use bunches from SPS** with 3.5 E11 protons every ~5sec, → electron beam of up to O (50GeV).
  →Search for dark photons a la NA64, 3 orders of magnitude increase in electrons

- Using the **LHC beam as a driver**, TeV electron beams are possible → Electron/Proton or Electron/Ion Collider
  - **LHeC like collider**: E_e up to O (50 GeV), colliding with LHC protons → exceeds HERA centre-of-mass energy
  - **VHPeC:** choose E_e = 3 TeV as a baseline and with E_P = 7 TeV yields $\sqrt{s}$ = 9 TeV. → CM ~30 higher than HERA. Luminosity ~ $10^{28} - 10^{29}$ cm^{-2} s^{-1} gives ~ 1 pb−1 per year.



G. Xia et al., Nucl. Instrum. Meth. A 740 (2014) 173.



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