AWAKE

MPP Project review

13/12/2021

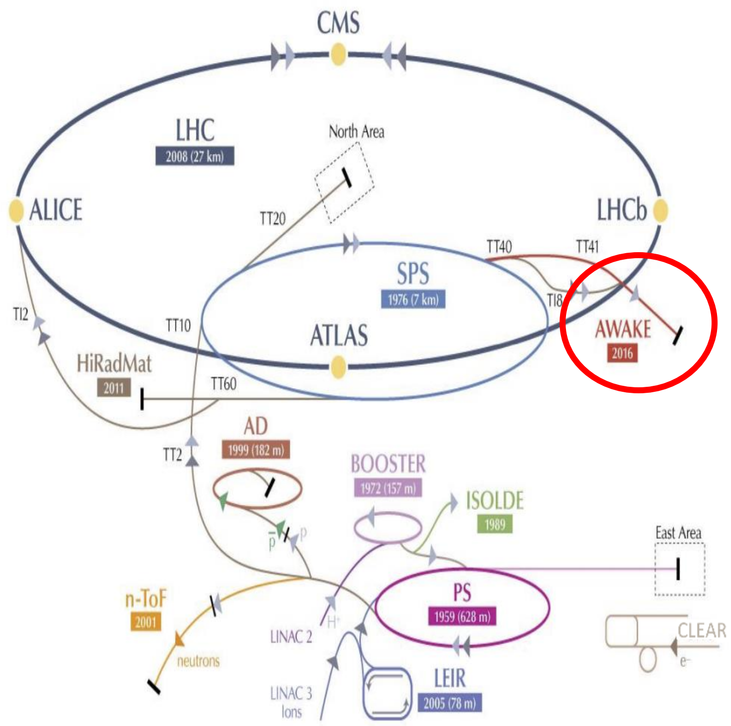
Michele Bergamaschi

MAX-PLANCK-INSTITUT FÜR PHYSIK

Contents

AWAKE Advanced WAKefield Experiment

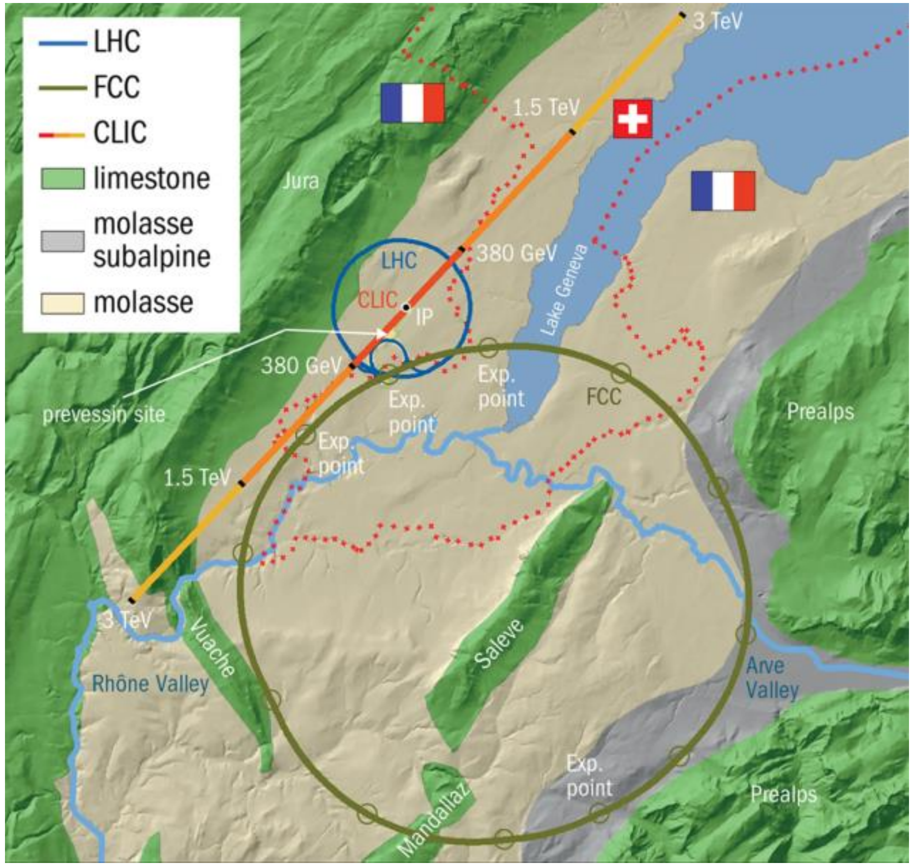
Plasma wakefield experiment at CERN



Collaboration of 23 institute worldwide :
Max-Planck-Institut für Physik is one of the key contributor

Plasma wakefield acceleration

High Energy physics requires ultra-relativistic accelerated particles



Maximum energy delivered to the particle is limited by:

- acceleration gradient mainly for linear accelerator
- bending dipole field in circular accelerator (hadron)
- synchrotron radiation losses in circular accelerator (electrons)
- maximum accelerator (tunnel) size

Plasma wakefield acceleration

Classics accelerators have limited acceleration gradient based on RF cavities limited accelerator gradient. The limit of the order of 100 MV/m due to electrical breakdown in the cavities

Use of plasma as it is already ionized i.e. conductor and can sustain voltage up to 10 GV/m

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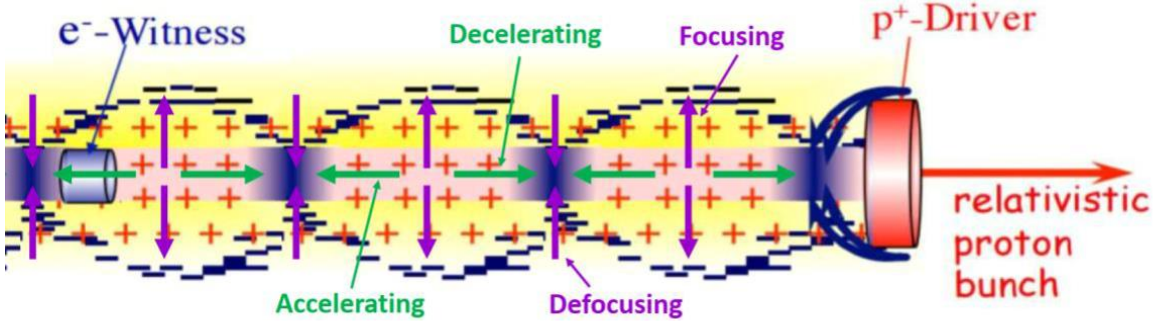
Plasma wakefield acceleration

A laser pulse or a charged particle that travel inside the plasma can induce a modulation of the plasma electron density that sustains longitudinal and transverse field which are called **wakefield**



Wakefield can be used to accelerate particles

At AWAKE we use proton bunch from the SPS as driver and electron bunch witness externally injected

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Why a proton Plasma Wakefield Accelerator?

PW laser ≈ 40J/Pulse

FACET (electron PWFA) ≈ 30J/Pulse

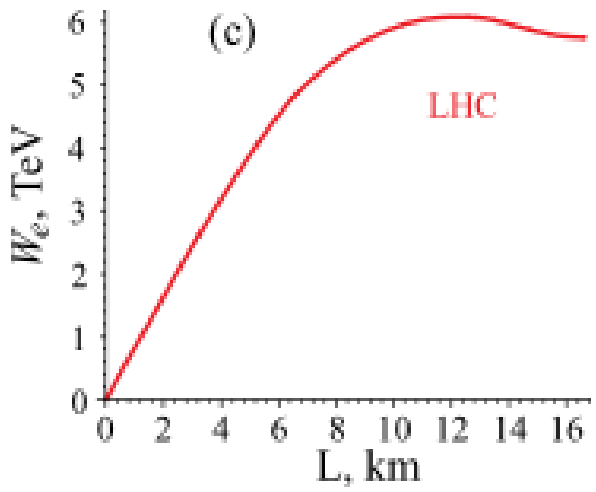
SPS 19 kJ/bunch

LHC 112kJ/bunch

} High energy in a single plasma stage

Energy gain
LHC bunch

TeV in km ≈ GV/m



A. Caldwell, & K. Lotov, (2011). Plasma wakefield acceleration with a modulated proton bunch, *Physics of Plasmas*, *18*(10), 103101

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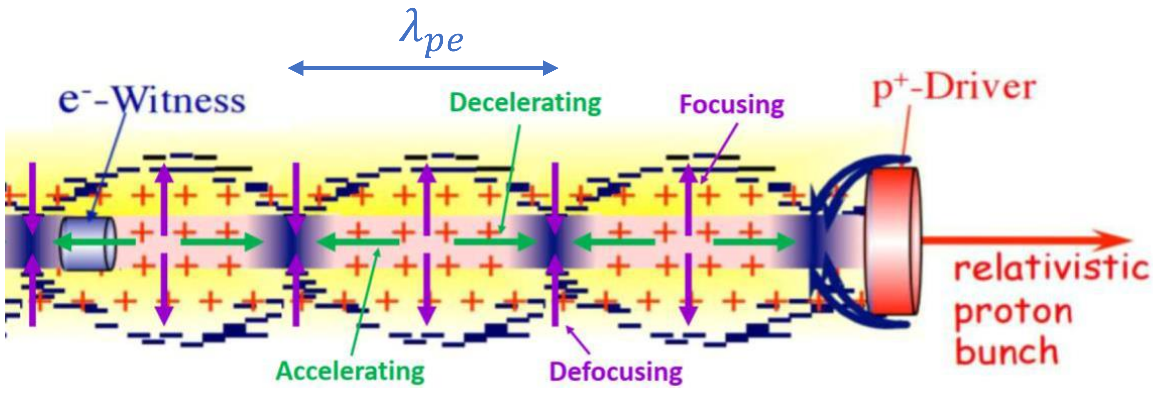
To efficiently drive wakefield the proton bunch should have: $\sigma_r \approx \frac{\lambda_{pe}}{2\pi}$ $\sigma_z \approx \frac{\lambda_{pe}}{2\pi}$

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

For SPS:

$$\sigma_r \approx 200\ \mu m \ \Rightarrow n_e \approx 7 \cdot 10^{14} cm^{-3}$$

$$\sigma_z \approx 7\ cm \ \gg \lambda_{pe}$$



Self-Modulation Instabilities (SMI)

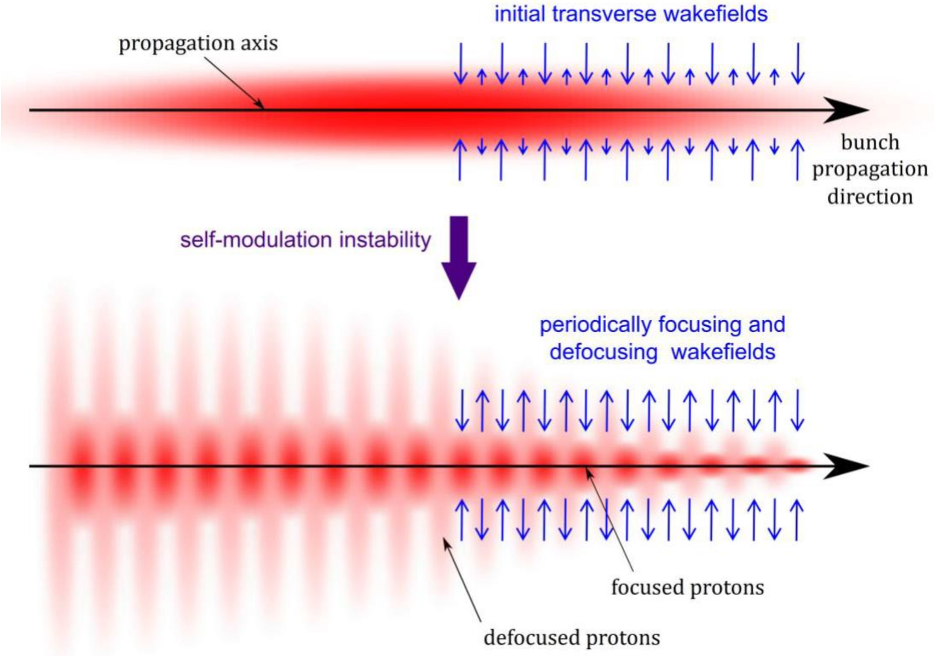


Image from F. Batch *PhD thesis*

MPP AWAKE

- **PhD Students**
  - **Pablo Irael Morales Guzmàn**
  - **Jan Pucek**
  - **Livio Verra**
  - **Tatiana Nechaeva**
  - Fabian Batsch
  - Anna Maria Bachmann } Graduated in 2021
  - Vasyl Hafych } Thesis submitted in 2021

- **Postdocs**
  - **Michele Bergamaschi**
  - **John Farmer**
  - Mathias Hüther
  - Joshua Moody } Left the group in 2021

- **Faculty**
  - **Patric Muggli**
  - **Allen Caldwell**

AWAKE Run 1 (2016-2018)

Awake Run 1 goals:

1. Demonstrate and study the seeded self-modulation (SSM) of the long SPS proton bunch in a dense plasma: $\sigma_z \gg \lambda_{pe} \approx {n_e}^{-1/2}$
2. Accelerate externally injected electrons to the GeV energy level

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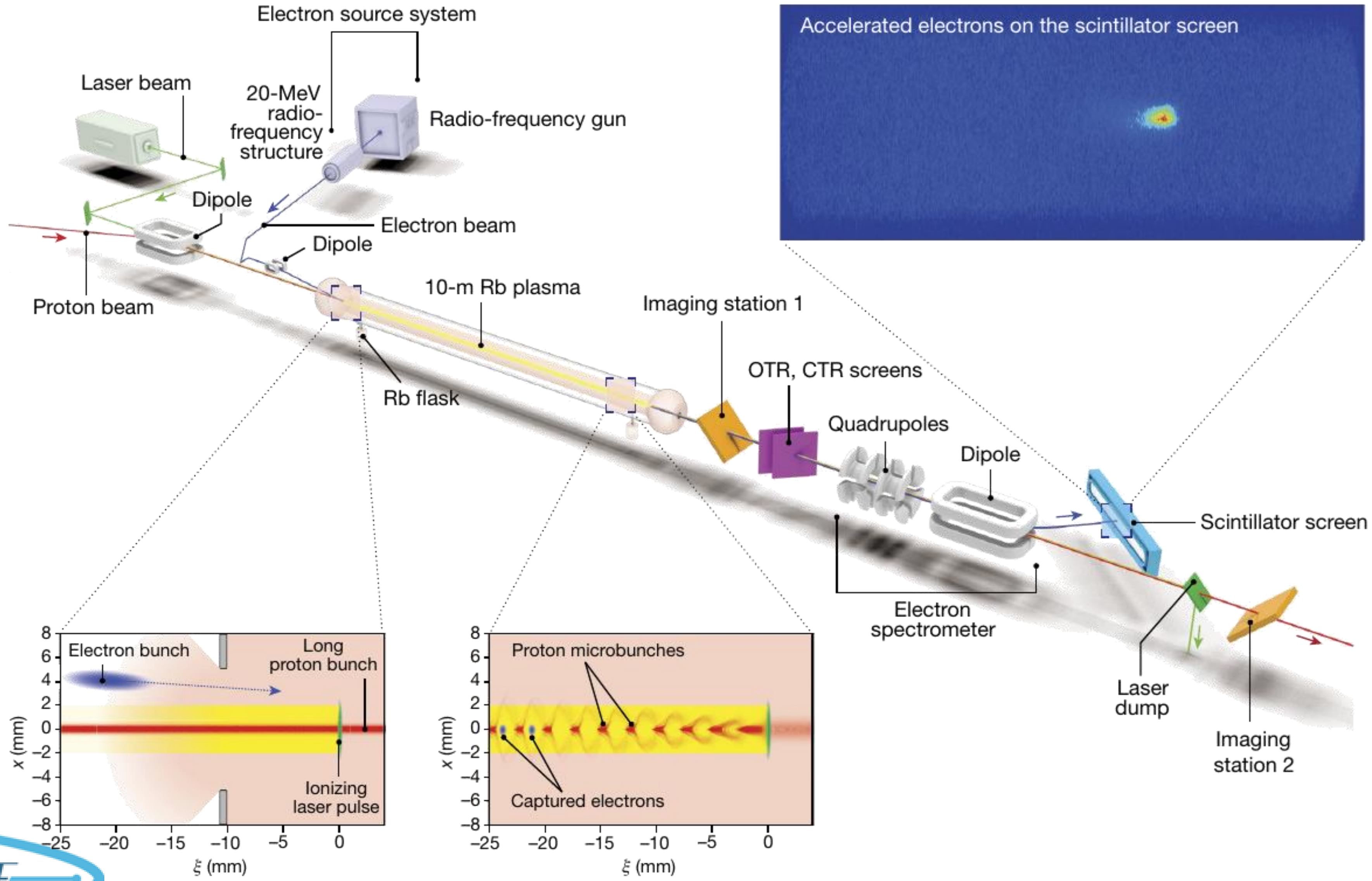
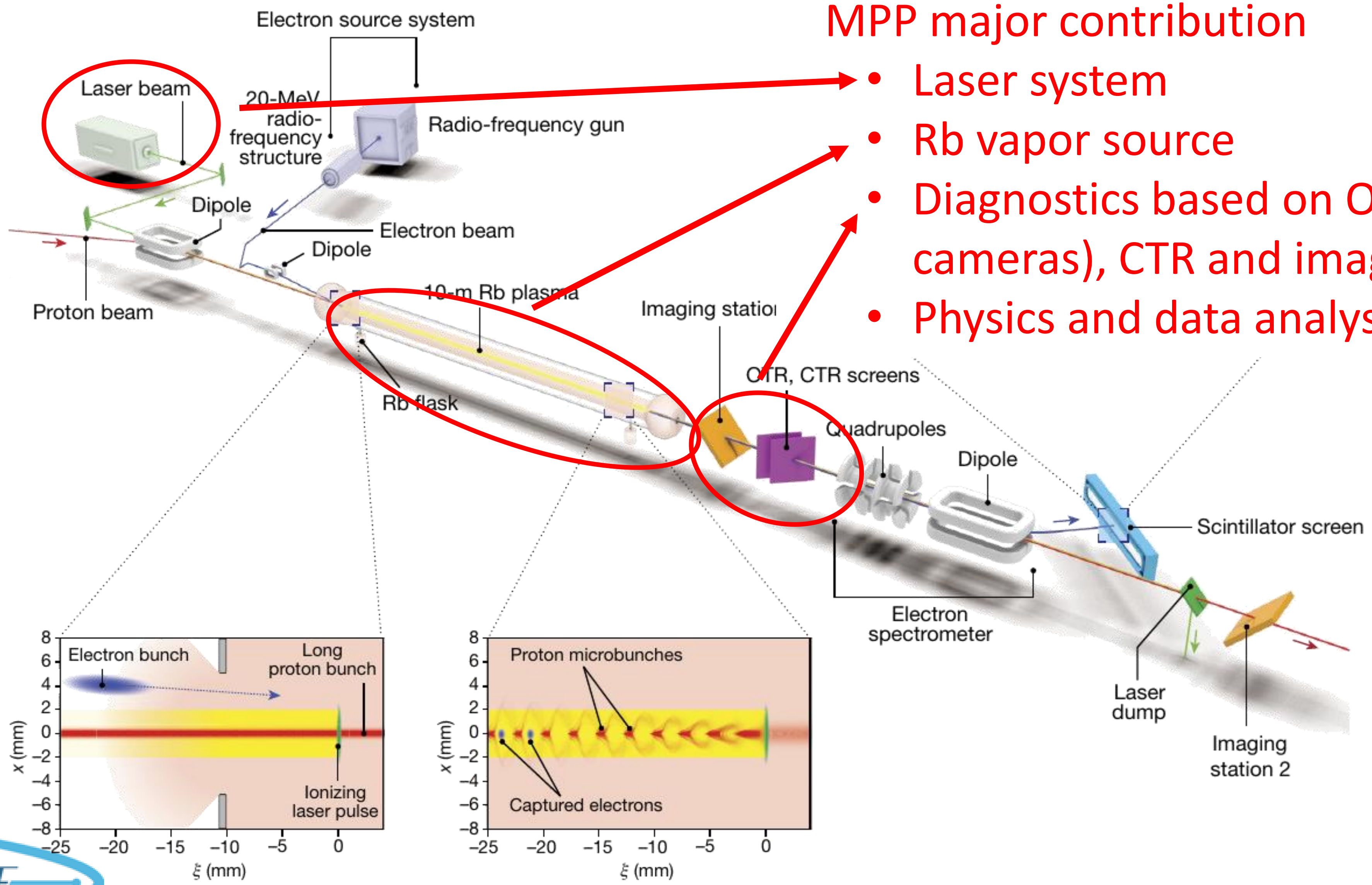
AWAKE Run 1 (2016-2018)



[AWAKE collaboration, *Acceleration of electrons in the plasma wakefield of a proton bunch*, **Nature 561,** 363–367 (2018)]

AWAKE Run 1 (2016-2018)



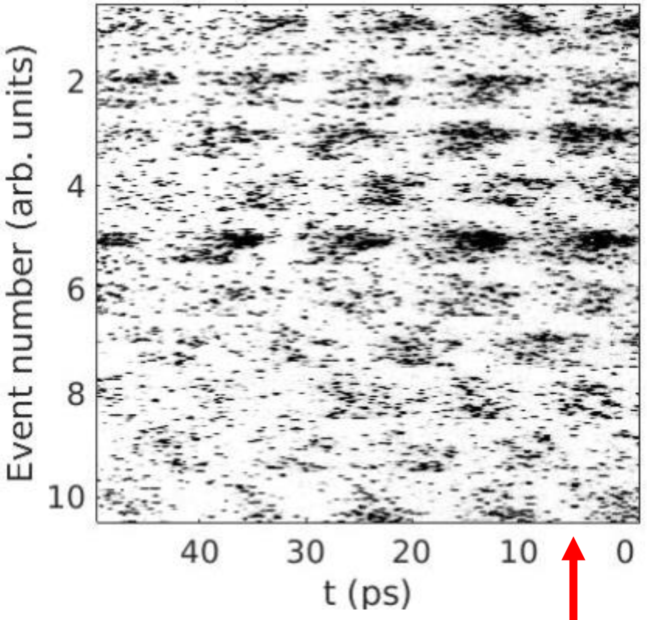
MPP major contribution

- Laser system
- Rb vapor source
- Diagnostics based on OTR (streak cameras), CTR and imaging
- Physics and data analysis

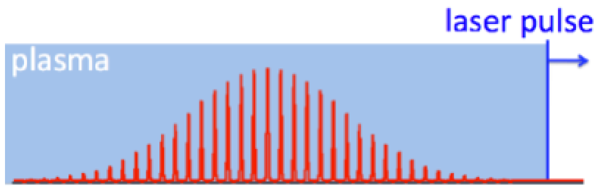
AWAKE collaboration, *Acceleration of electrons in the plasma wakefield of a proton bunch*, **Nature 561,** 363–367 (2018)

AWAKE Run 1 (2016-2018)

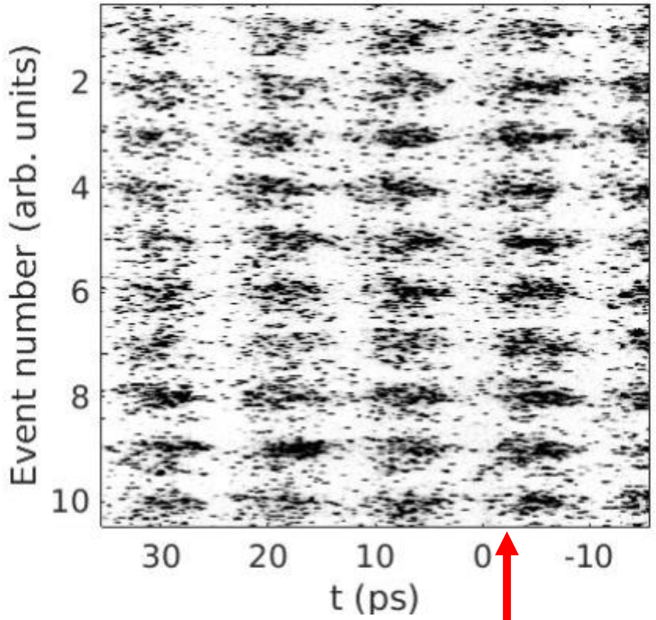
Self-Modulation Instabilities (SMI)



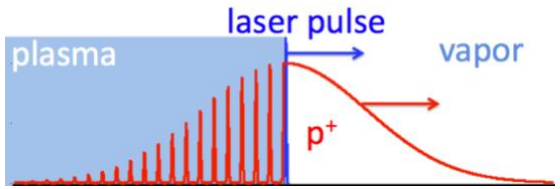
not reliable e^- acceleration

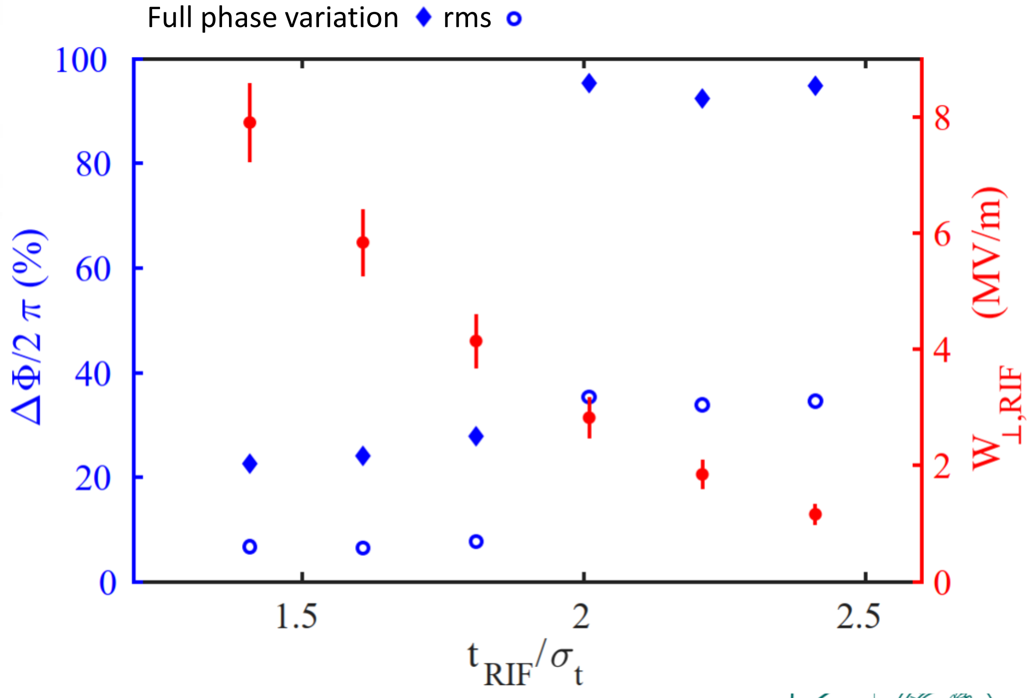


Seeded Self-Modulation (SSM)



possible e^- acceleration





F. Batsch et al., *Phys. Rev. Lett.* 126, 164802, 2021

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AWAKE Run 2 (2021-)

Awake Run 2 :

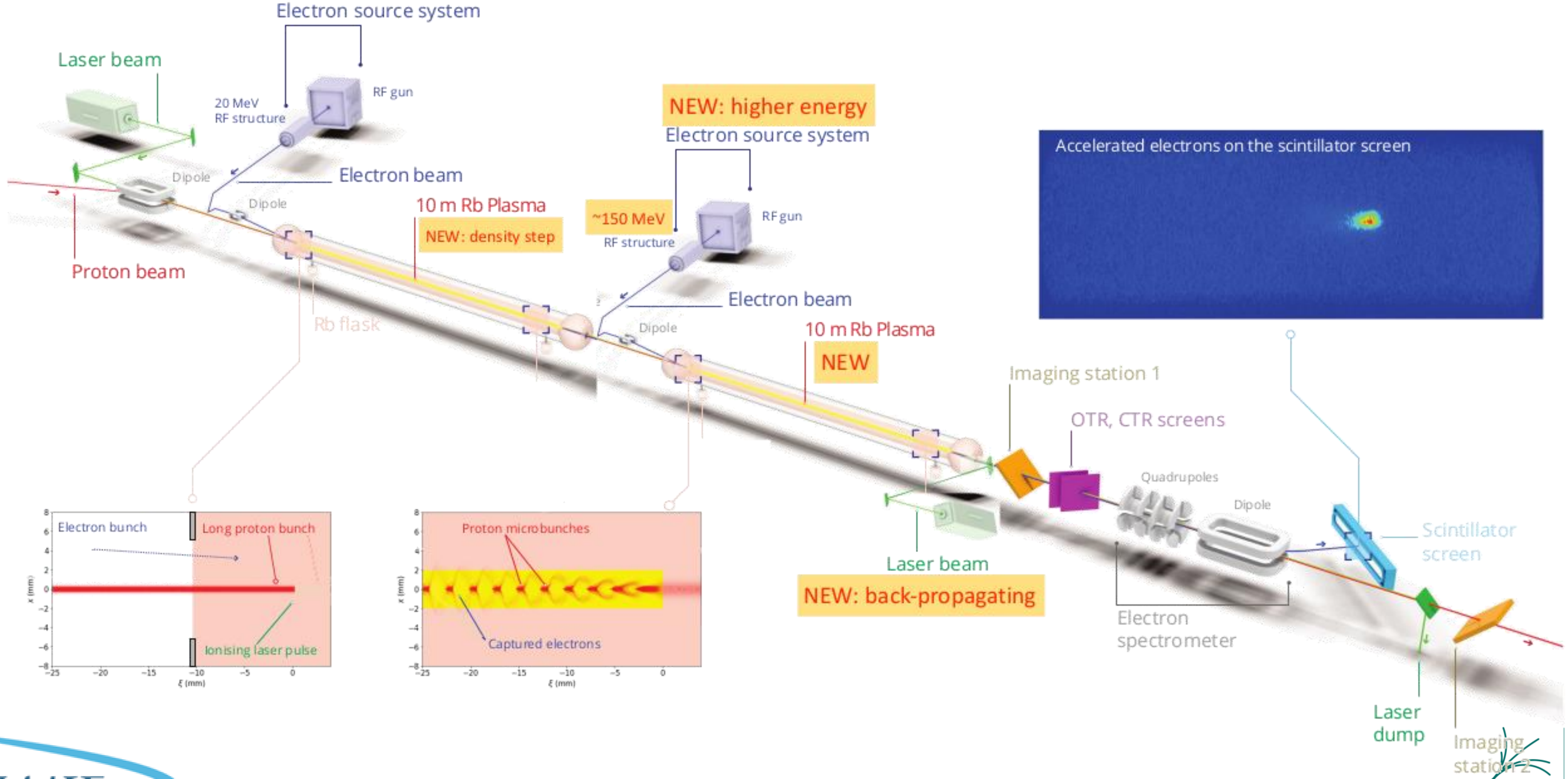
From Acceleration to Accelerator

1. Demonstrate acceleration of externally injected electron bunch
2. Plasma source scalability and acceleration

Four phases:

• **seeding** proton bunch modulation with an **electron bunch** (2a)	2021-2022
• **plasma cell with density step** to stop the evolution of the modulation (2b)	2023-2024
• inject electrons & accelerate with limited emittance blowup (2c)	After LHC LS3
• implement scalable plasma cell technologies (2d)	After LHC LS3

AWAKE Run 2 (2021-)



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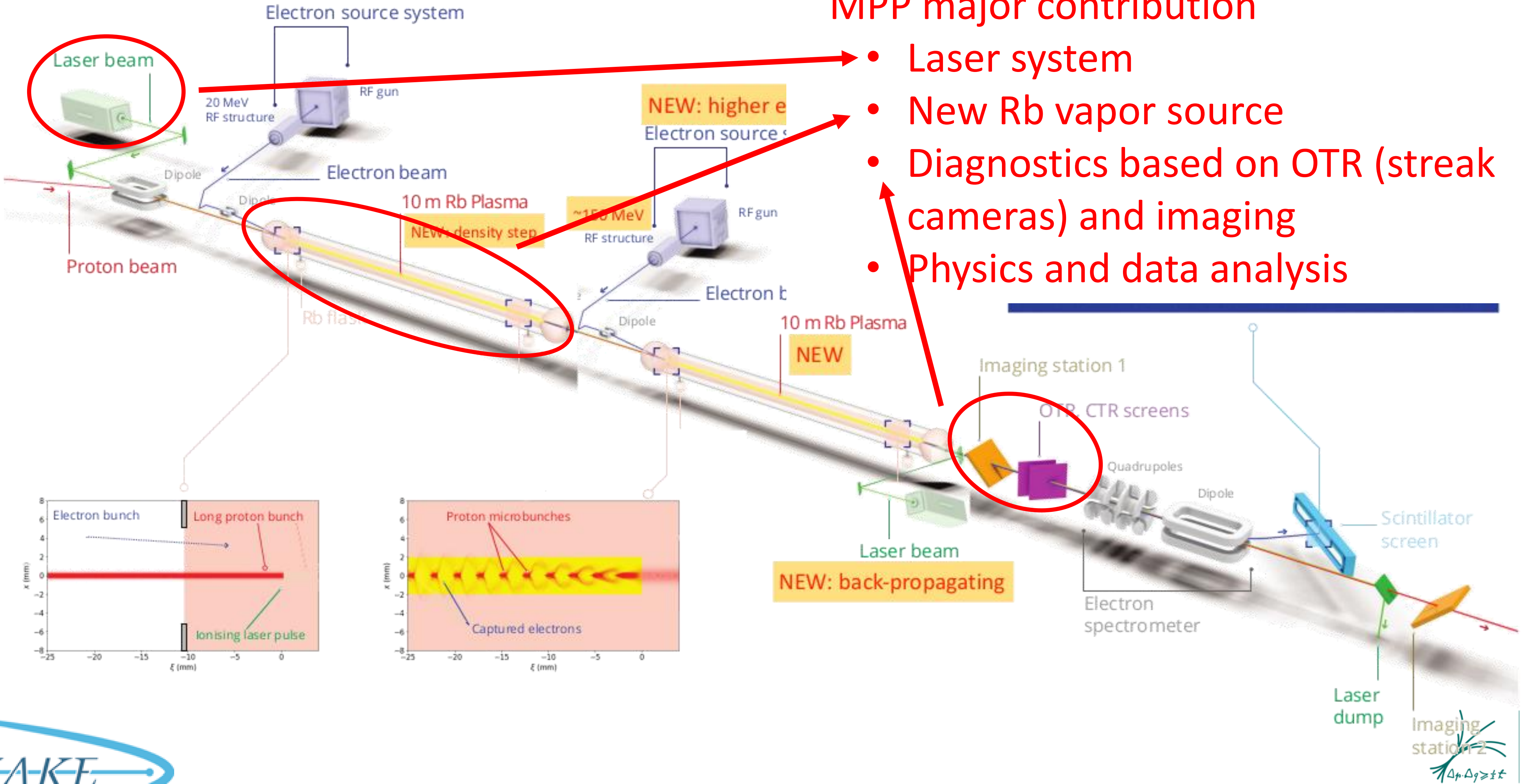
AWAKE Run 2 (2021-)

MPP major contribution

- Laser system
- New Rb vapor source
- Diagnostics based on OTR (streak cameras) and imaging
- Physics and data analysis



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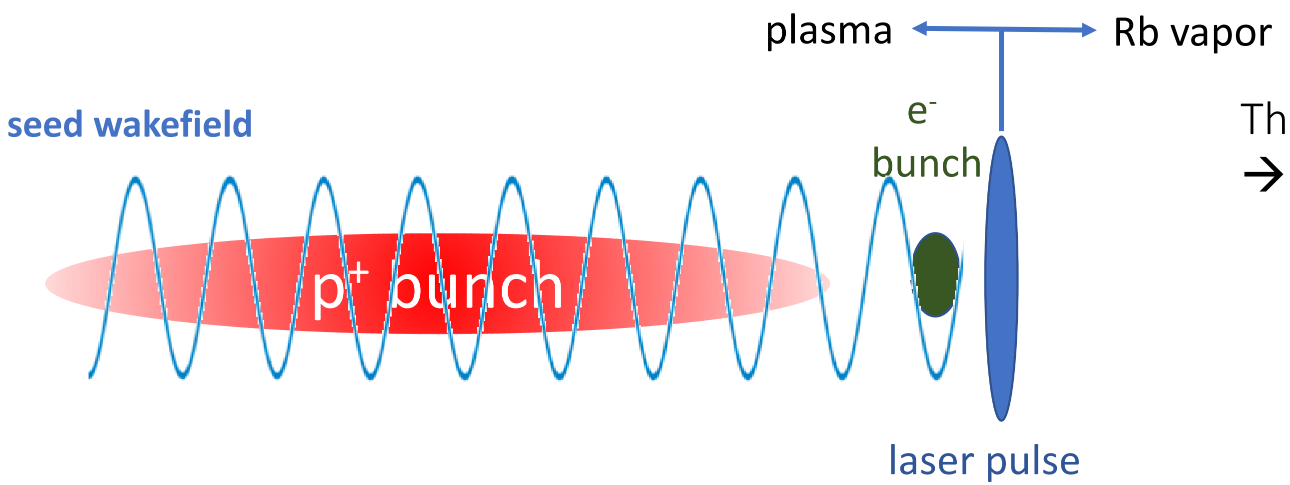
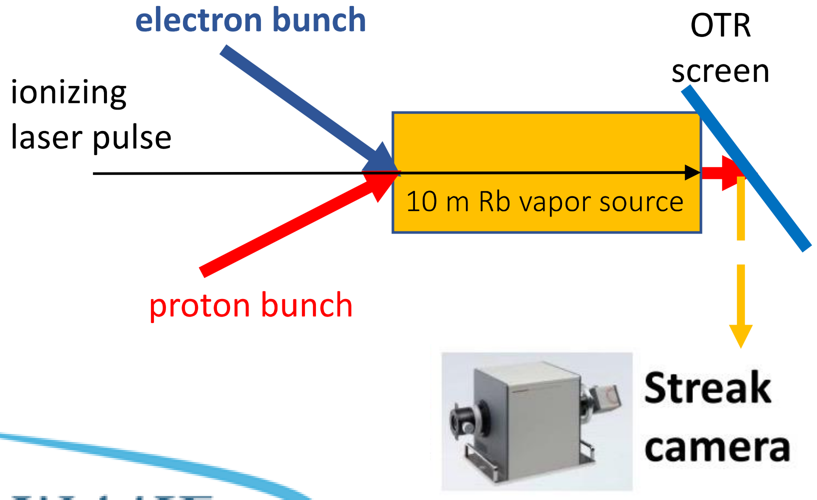
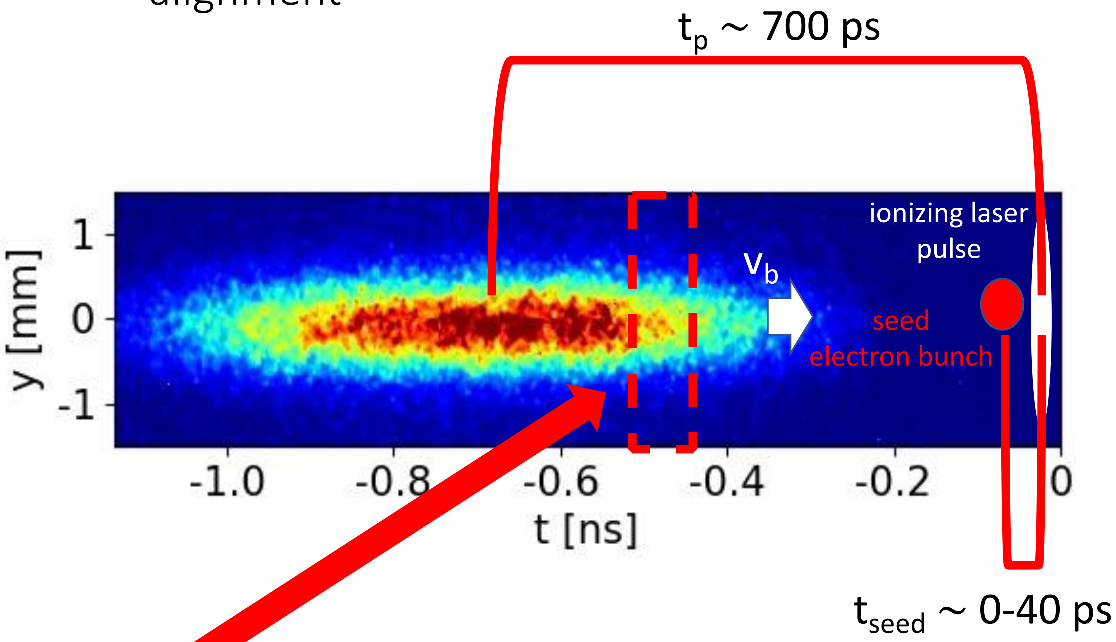
Electron bunch seeding Livio Verra



The electron bunch provides the seed wakefield
→ seeding relies on the electron bunch properties:

- bunch charge density
- energy
- alignment





To prove that the electron bunch seeds SM:
→ study the time structure of the microbunch train at the ps time scale

Electron bunch seeding: timing **reproducibility**

Livio Verra

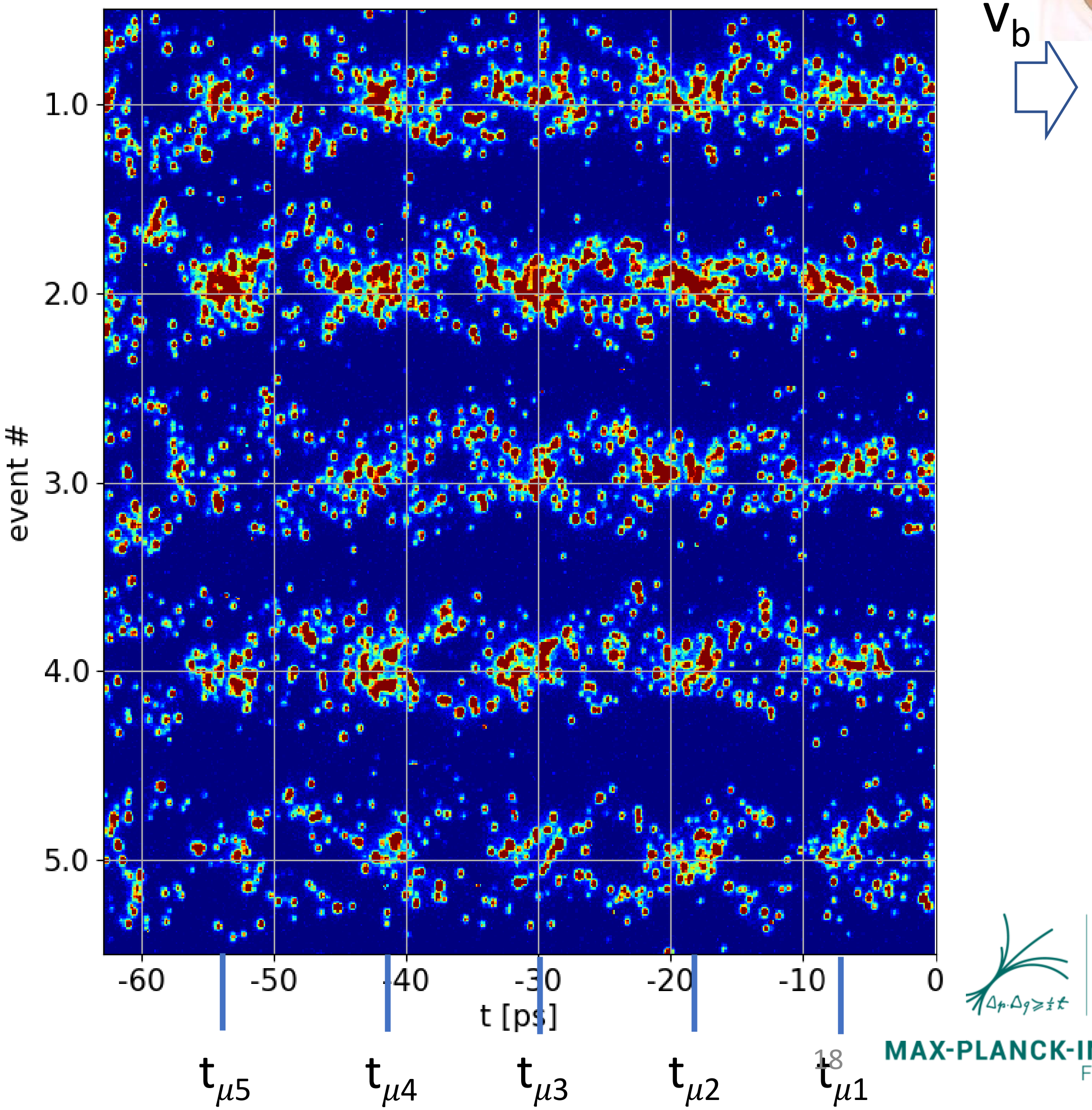
proton bunch population = $1.0 \cdot 10^{11}$ ppb
73 ps streak camera window
electron bunch charge Q = 220 pC
$n_{pe} = 1 \cdot 10^{14}\ cm^{-3}$
→ f_{pe} = 89.7 GHz
T_{pe} = 11.1 ps

The microbunches appear at the same time t_μ along the bunch event after event

rms(t_μ) / T_{pe} ~ 0.09

Self-Modulation of the proton bunch is seeded by the electron bunch!

Waterfall plot of single images



L. Verra et al., in preparation

Electron bunch seeding: timing **reproducibility** Livio Verra

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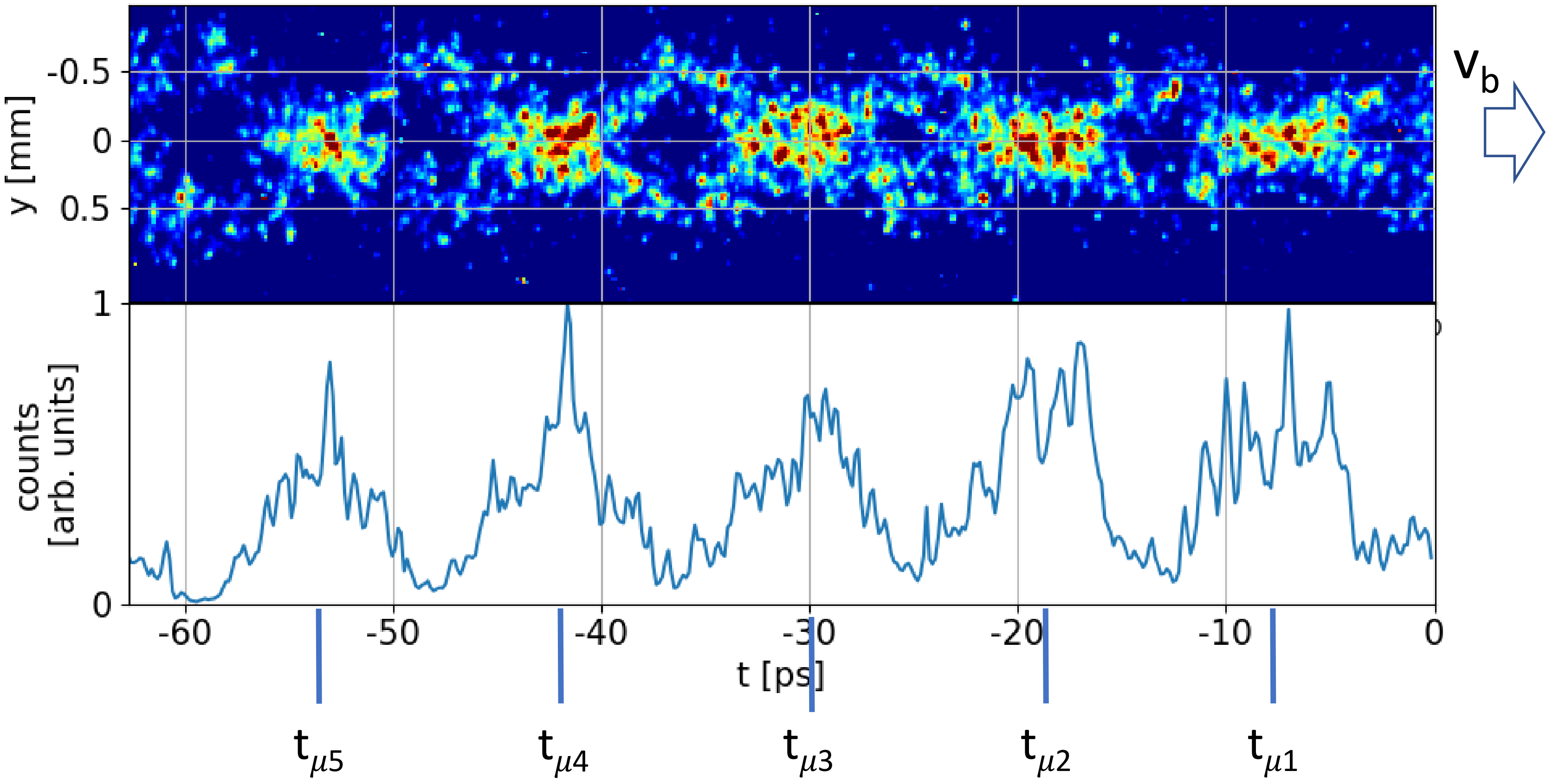
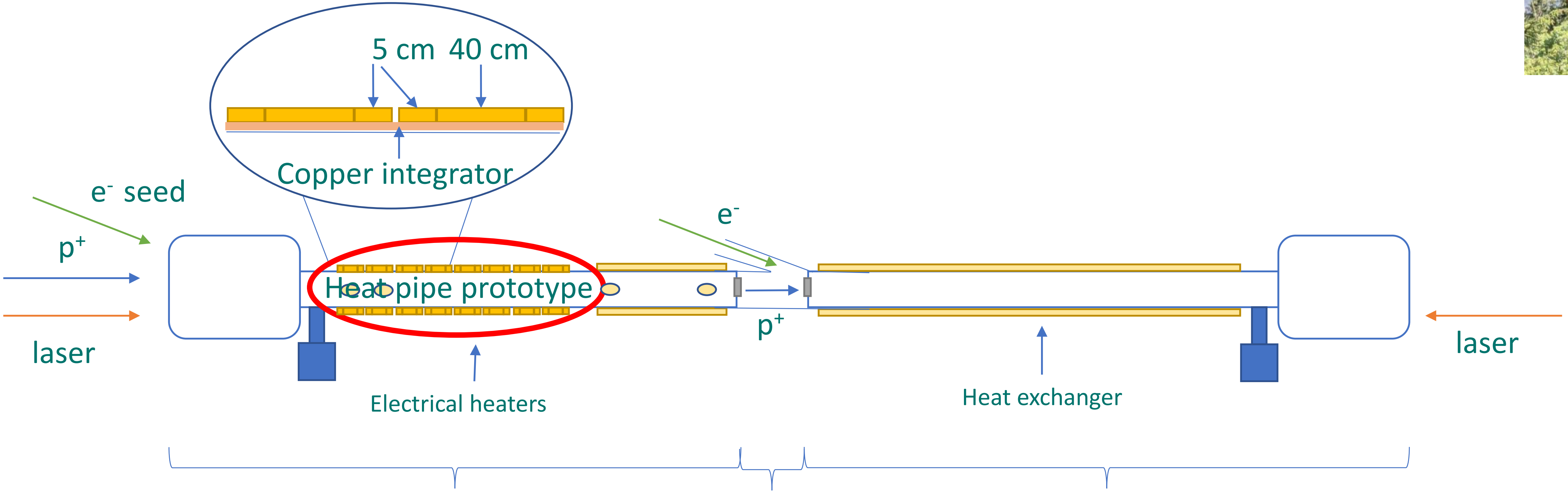
sum of the 10 events



L. Verra et al., in preparation

Development of density step Rb vapor source Michele Bergamaschi



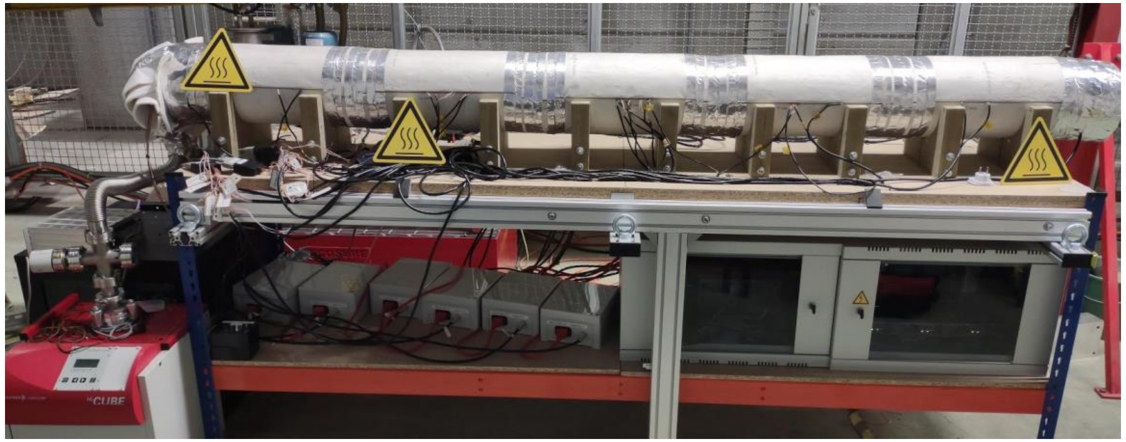
- Length: ~ 10 m
- Step location each 50 cm from 0.5 to 4 meters
- Step height up to ±10%

- Length: 10 m
- Galden heating only
- Density measurement at up to two positions

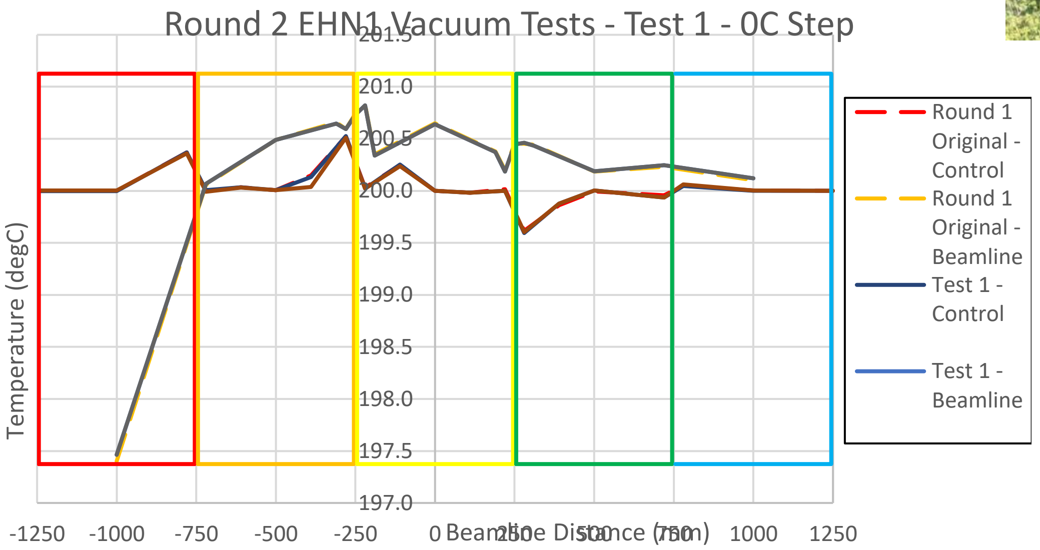
*not to scale

Development of density step Rb vapor source Michele Bergamaschi

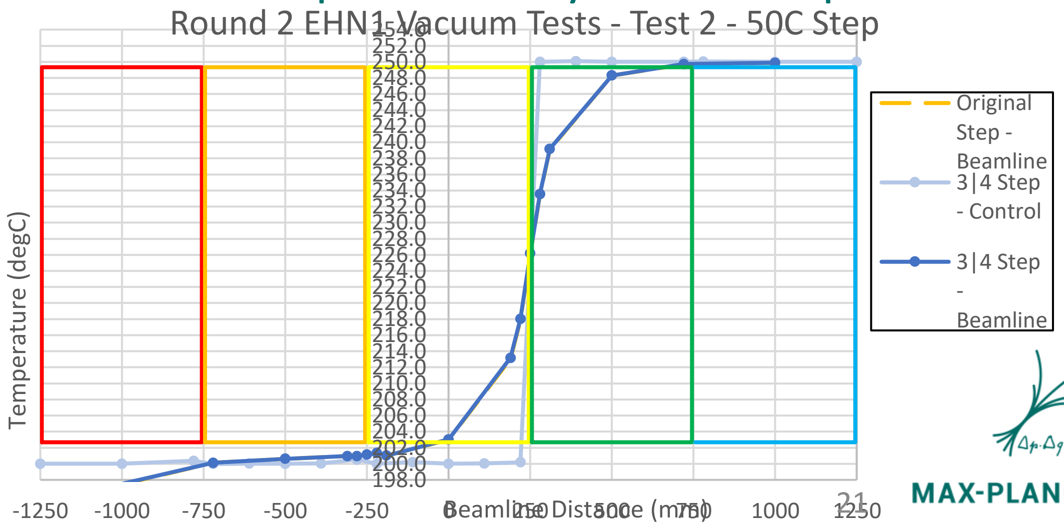
- Stand alone electrically heated section with 5 zones
- Installed and tested at CERN (EHN1)



Flat profile 1°C ≈ 0.2% $\delta T\ (^{o}K)/T(^{o}K)$



Excellent Reproducibility – 50°C Step



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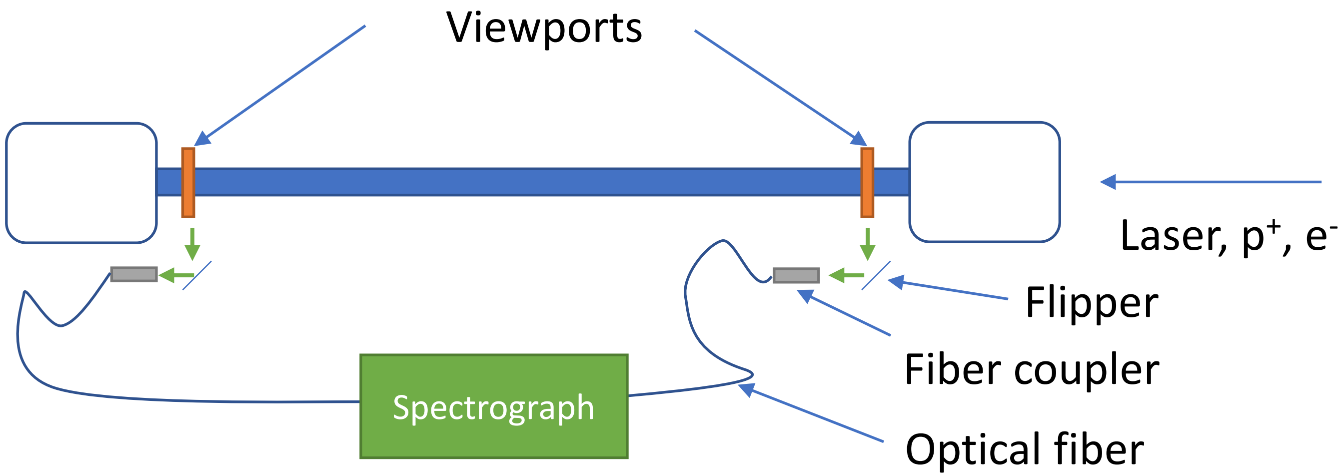
Plasma light diagnostic P. Muggli M. Bergamaschi J. Pucek



Idea of using plasma light to observe Wakefield amplitude

Preliminary analysis and results:

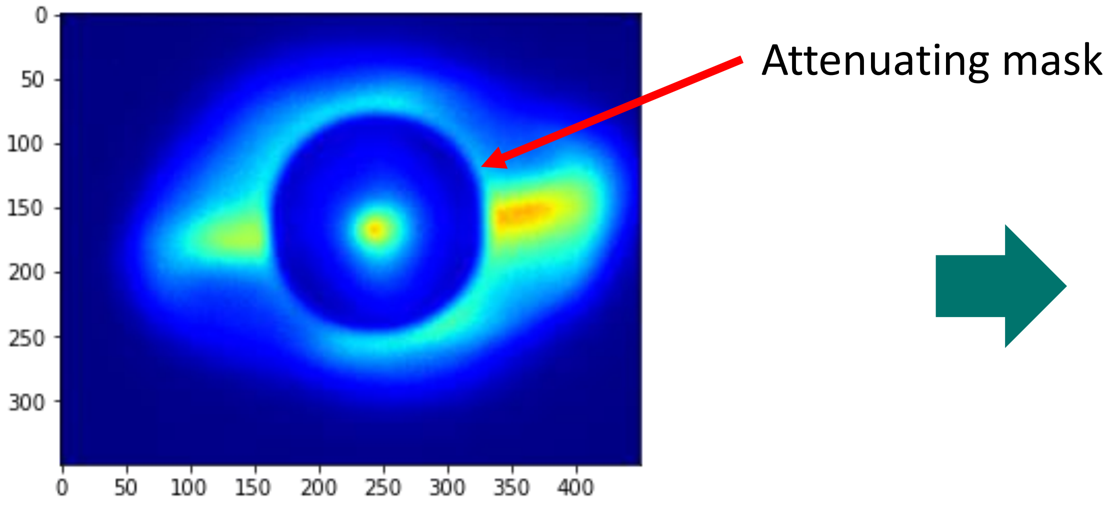
- No Rb Vapor – laser pulse observed and isolated in time
- With Rb Vapor – plasma light observed after laser pulse
- With Proton in plasma, signal increased of 2 order of magnitude
- Sign of transition between SMI and SSM

Spectrograph is used at 0th order

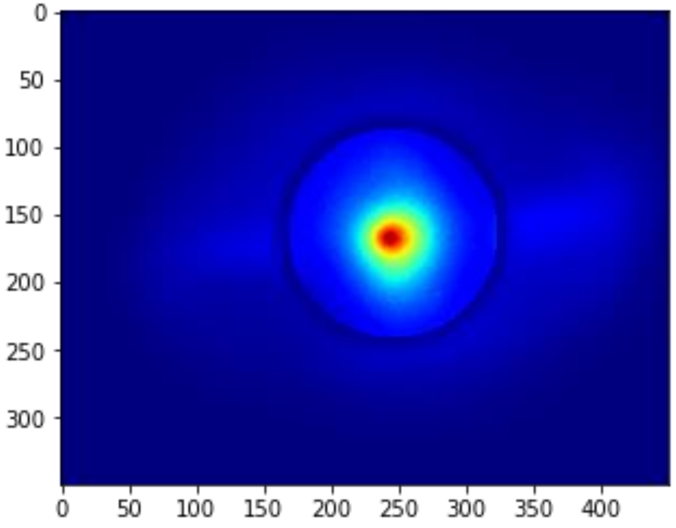
Future upgrade plans to use photo-multiplier tubes

Upgrade the halo monitor Jan Pucek

Proton beam imaged with OTR scintillator screen
After passing through the plasma



Reconstructed mask attenuation



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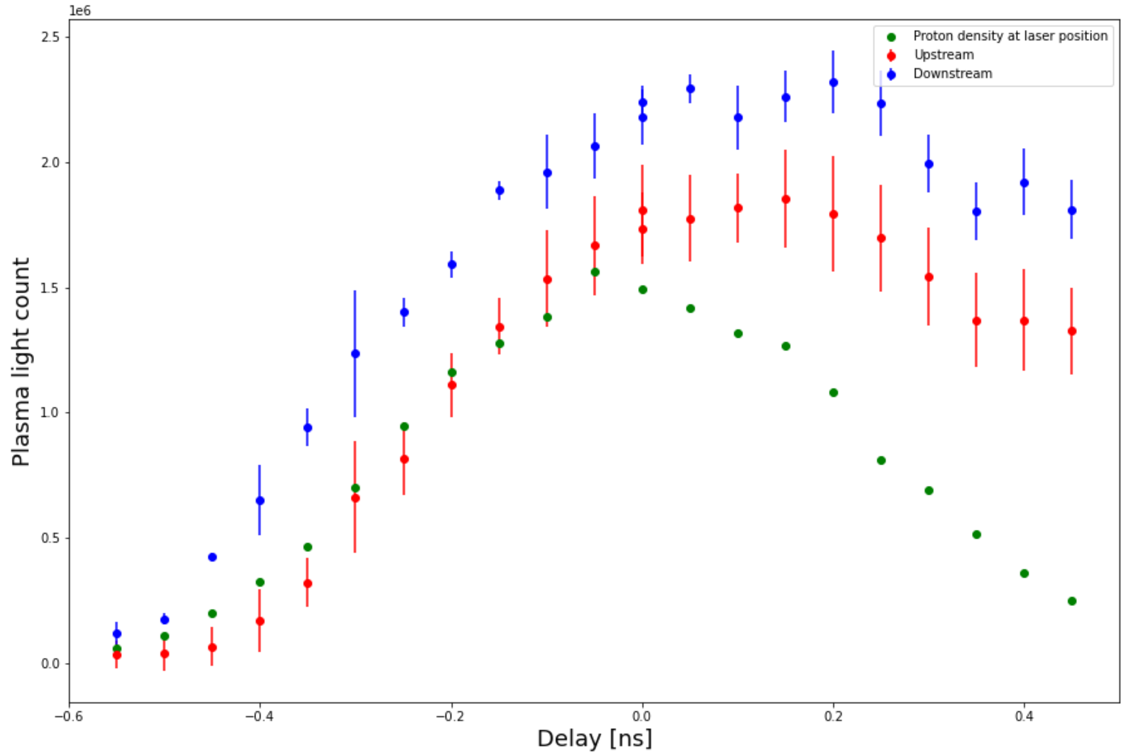
Competition between SMI and eSSM Jan Pucek

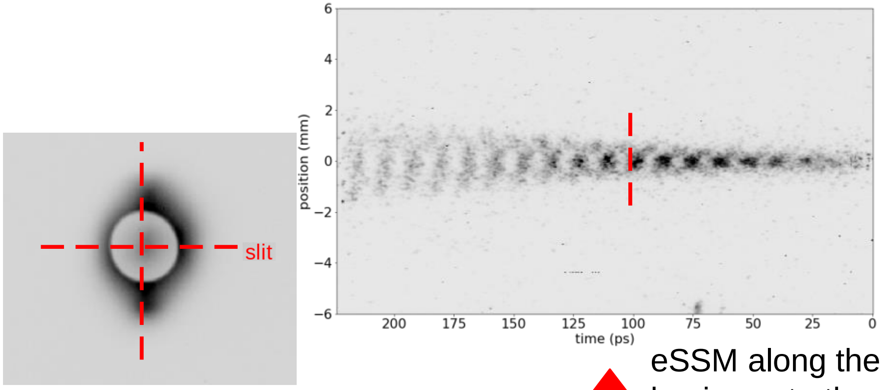


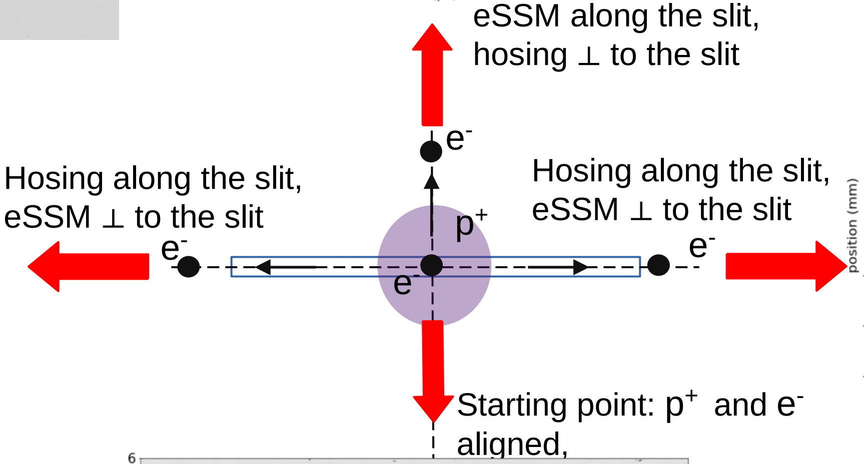
Plasma light measurement where the seed position was changed (x-axis)
Points towards constant noise amplitude in front of the proton bunch
(to be verified)

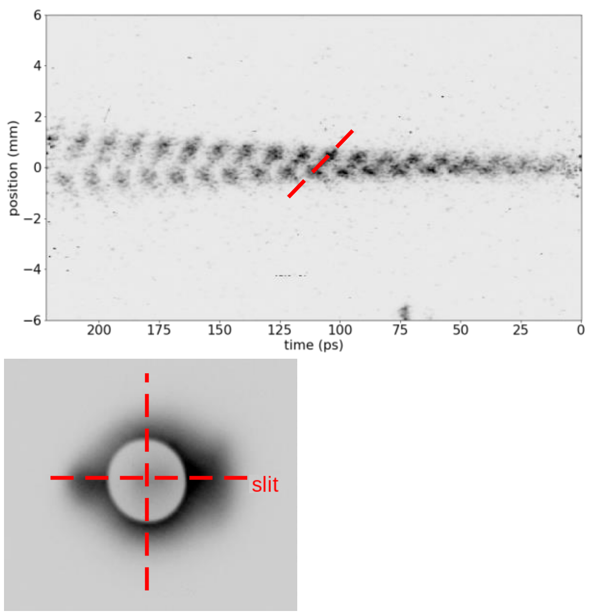
Seeding hosing instabilities with an electron bunch Tatiana Nechaeva

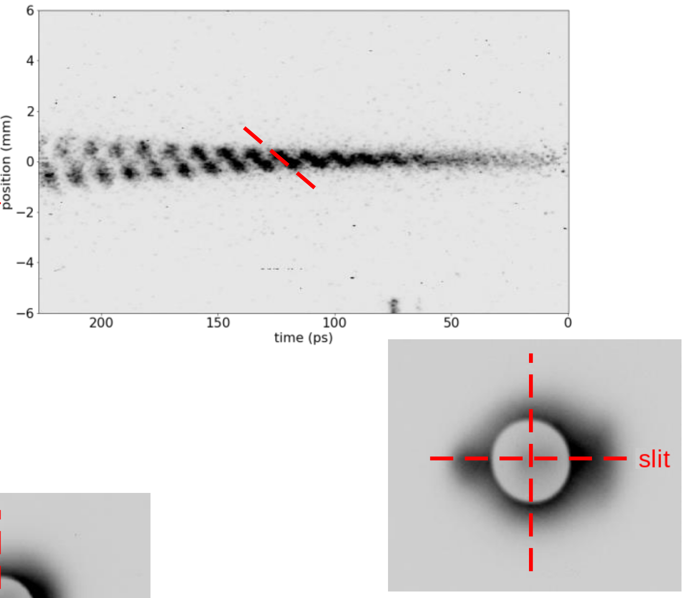
- Misalign e^- wrt p^+ along and across the streak camera slit
- This way coupling between self-modulation and hosing can be observed
- E-seeded hosing phase is reproducible!

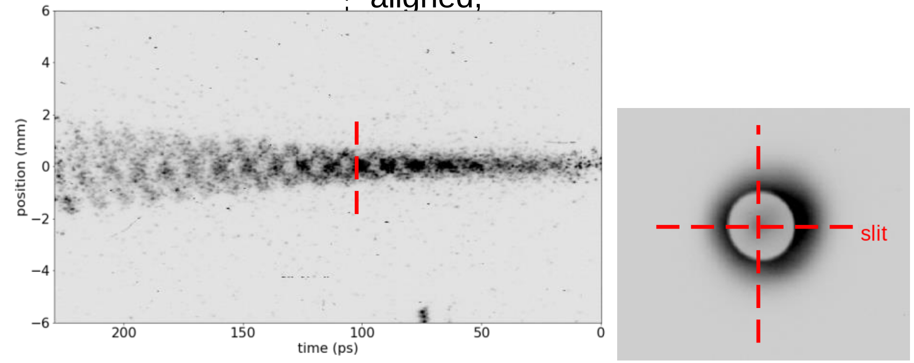
Streak camera images are sums of ~10 events





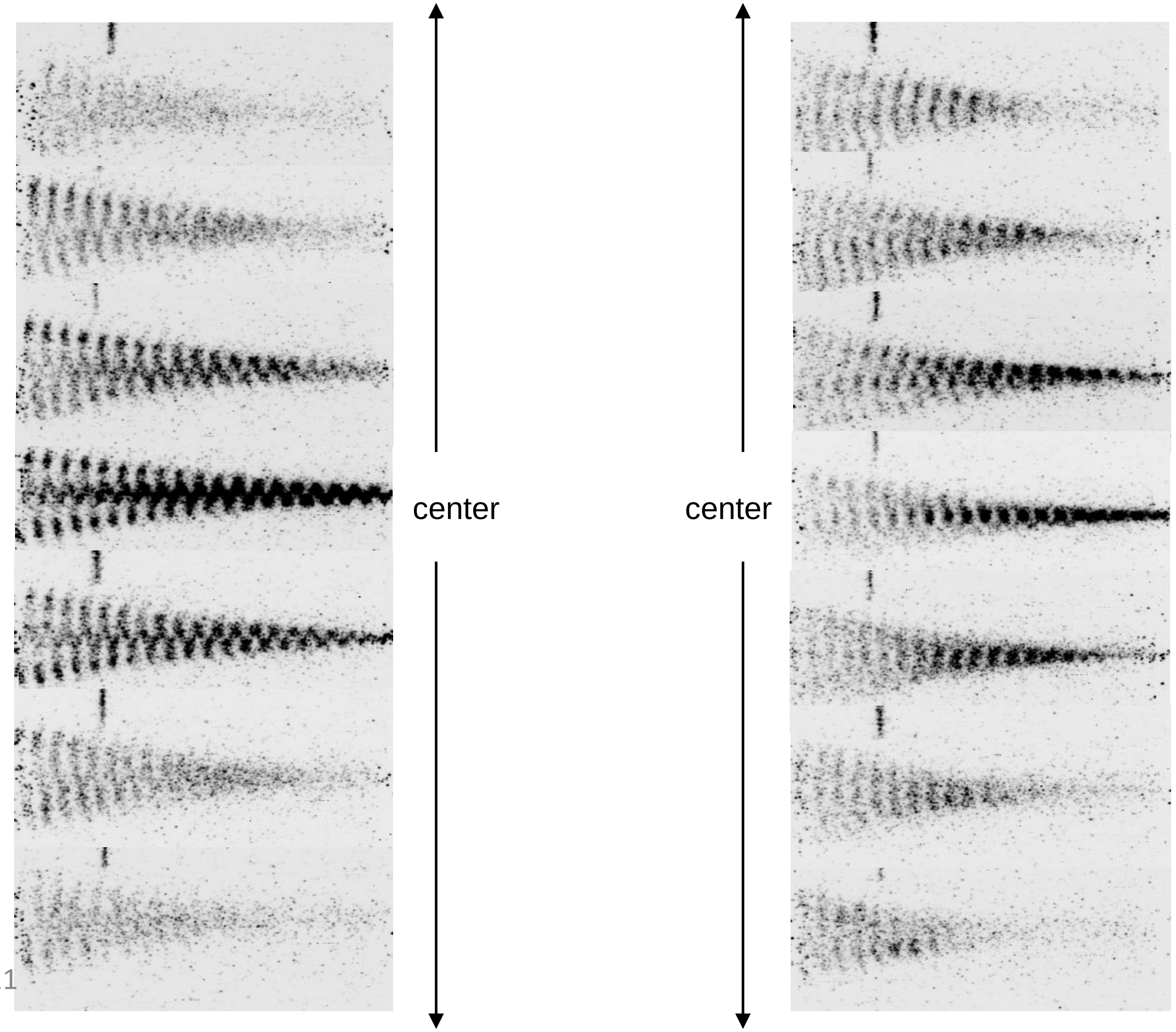




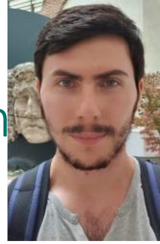


Seeding hosing instabilities with an electron bunch

- First 3D scans of hosing done
- This allows to look at possible features not visible in one plane and in the central slice of the distribution



Numerical* study of SM with plasma density gradients Pablo Guzm



PHYSICAL REVIEW ACCELERATORS AND BEAMS **24**, 101301 (2021)

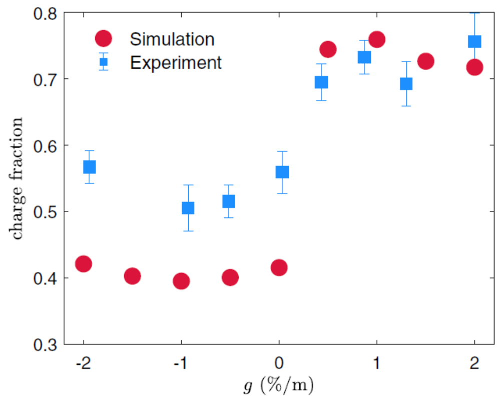
Simulation and experimental study of proton bunch self-modulation in plasma with linear density gradients

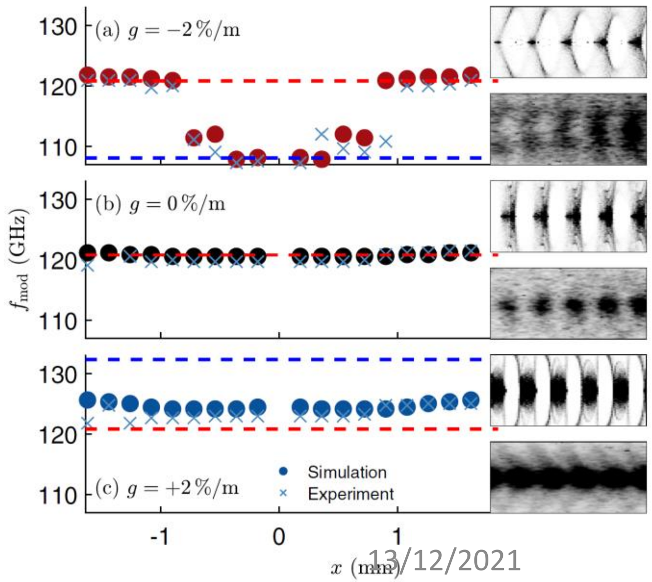
P. I. Morales Guzmán,[1,*] P. Muggli,[1] R. Agnello,[2] C. C. Ahdida,[3] M. Aladi,[4] M. C. Amoedo Goncalves,[3] Y. Andrebe,[2] O. Apsimon,[5,6] R. Apsimon,[6,7] A.-M. Bachmann,[1] M. A. Baistrukov,[8,9] F. Batsch,[1] M. Bergamaschi,[1] P. Blanchard,[2] F. Braunmüller,[1] P. N. Burrows,[10] B. Buttenschön,[11] A. Caldwell,[1] J. Chappell,[12] E. Chevallay,[3] M. Chung,[13] D. A. Cooke,[12] H. Damerau,[3] C. Davut,[6,14] G. Demeter,[4] A. Dexter,[6,7] S. Doebert,[3] J. Farmer,[3,1] A. Fasoli,[2] V. N. Fedosseev,[3] R. Fiorito,[6,5] R. A. Fonseca,[15,16] I. Furno,[2] S. Gessner,[3,17] A. A. Gorn,[8,9] E. Granados,[3] M. Granetzny,[18] T. Graubner,[19] O. Grulke,[11,20] E. Gschwendtner,[3] E. D. Guran,[3] V. Hafych,[1] J. R. Henderson,[6,21] M. Hüther,[1] M. Á. Kedves,[4] V. Khudyakov,[22,8] S.-Y. Kim,[13,3] F. Kraus,[19] M. Krupa,[3] T. Lefevre,[3] L. Liang,[6,14] N. Lopes,[16] K. V. Lotov,[8,9] M. Martyanov,[23] S. Mazzoni,[3] D. Medina Godoy,[3] J. T. Moody,[1] K. Moon,[13] M. Moreira,[16] T. Nechaeva,[1] E. Nowak,[3] C. Pakuza,[10] H. Panuganti,[3] A. Pardons,[3] A. Perera,[6,5] J. Pucek,[1] A. Pukhov,[22] B. Ráczkevi,[4] R. L. Ramjiawan,[3,10] S. Rey,[3] O. Schmitz,[18] E. Senes,[3] L. O. Silva,[16] C. Stollberg,[2] A. Sublet,[3] A. Topaloudis,[3] N. Torrado,[16] P. V. Tuev,[8,9] M. Turner,[3,24] F. Velotti,[3] L. Verra,[1,3,25] J. Vieira,[16] H. Vincke,[3] C. P. Welsch,[6,5] M. Wendt,[3] M. Wing,[12] J. Wolfenden,[6,5] B. Woolley,[3] G. Xia,[6,14] M. Zepp,[18] and G. Zevi Della Porta[3]

(AWAKE Collaboration)

Two groups:

- $g \leq 0$ %/m: low charge.
- $g > 0$ %/m: high charge.





- $g = -2$ %/m: modulation frequency varies with transverse direction, giving information of the self-modulation process along the plasma
- $g = 0, +2$ %/m: modulation frequency stays relatively constant

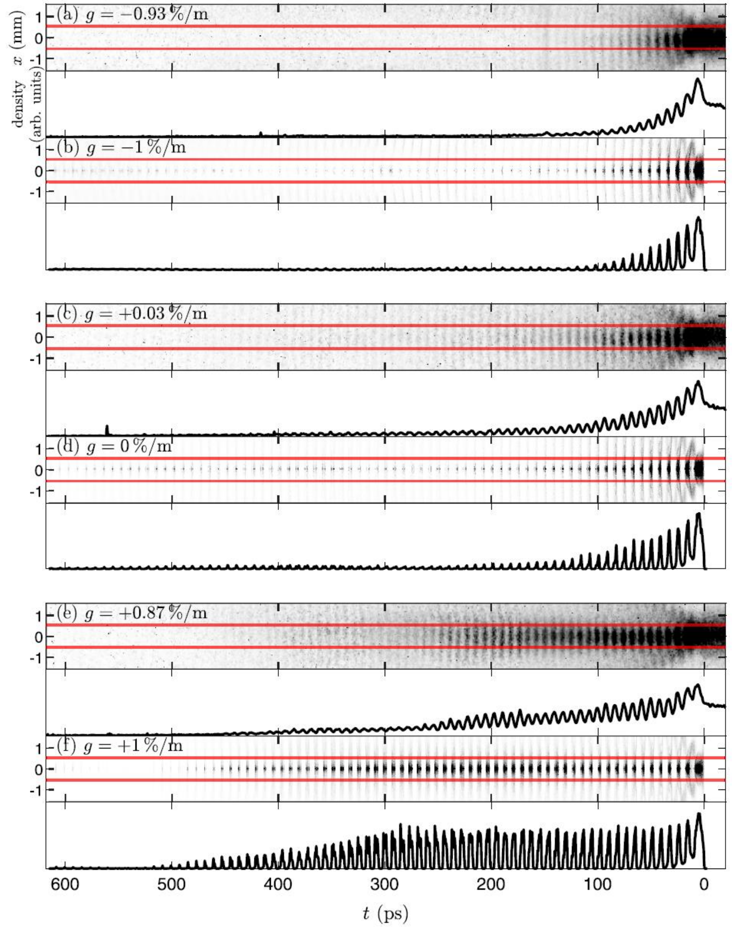
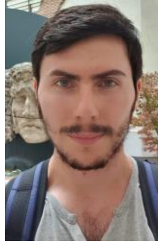


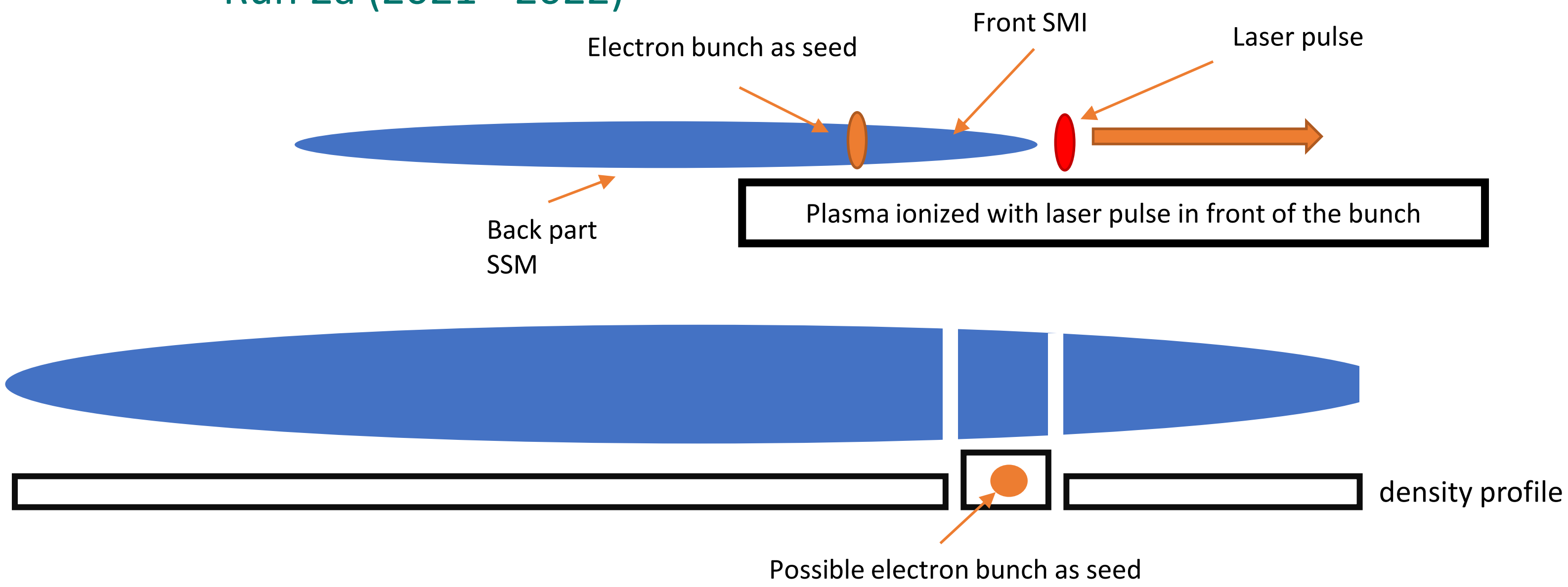
FIG. 1. Time-resolved experimental [(a), (c), (e)] and simulation [(b), (d), (f)] images and profiles of the modulated bunch with $g = -1$%/m [(a) and (b)], $g = 0$%/m [(c) and (d)], and $g = +1$%/m [(e) and (f)]. Longitudinal profiles obtained by summing counts within $\sigma_{r,\text{screen}}$: $|x| = \pm 0.536$ mm (red lines on image) of the axis. Images from 2D simulations are mirrored about the bunch axis for a more direct comparison with experimental ones.

* Osiris 4.0 http://epp.tecnico.ulisboa.pt/osiris

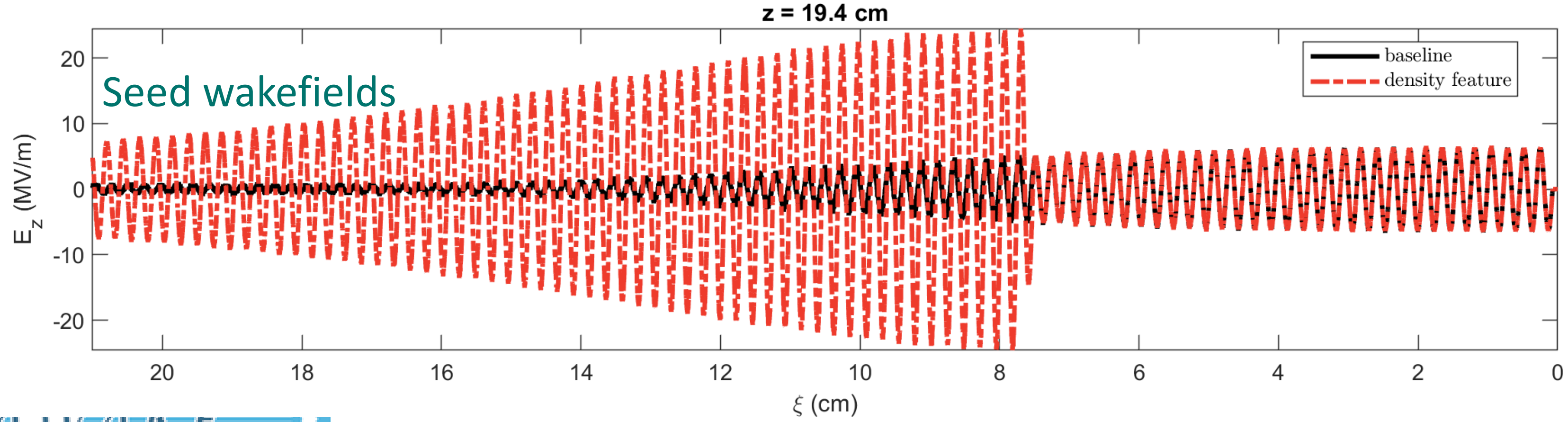
Interaction between developing wakefields Pablo Guzman

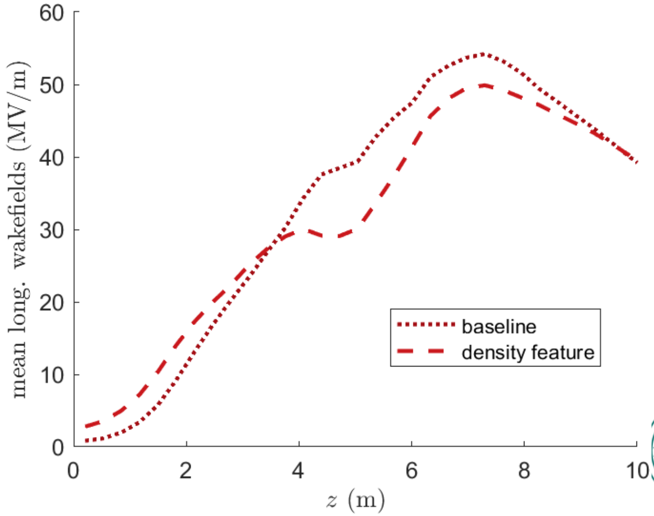


Run 2a (2021 - 2022)



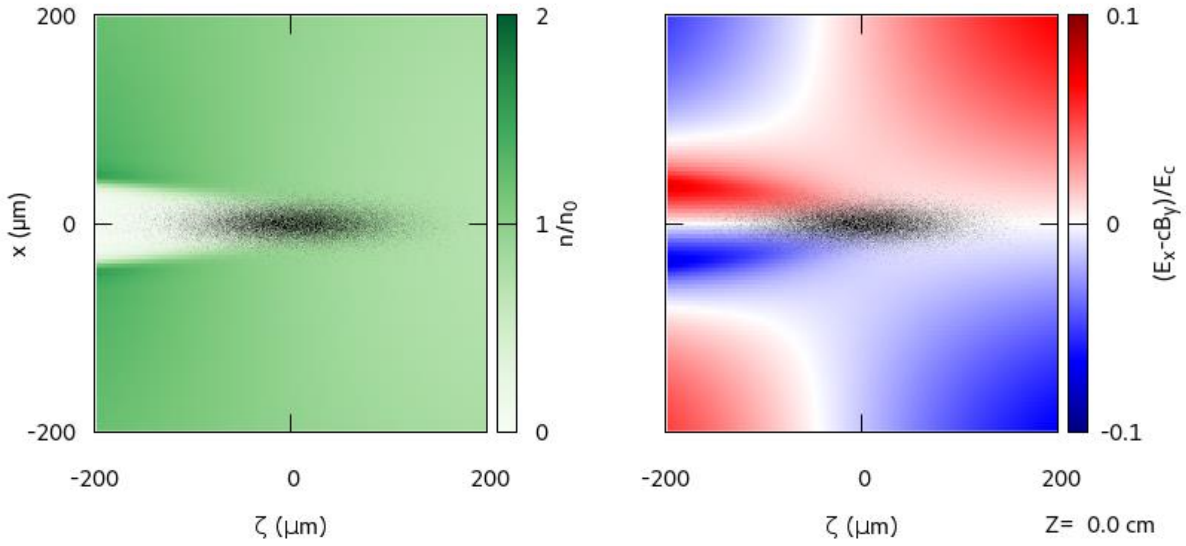
- Density feature inside of the proton bunch (can be replaced by an electron bunch)
- Understand influence of SM at the front on SM at the back during SM growth and evolution
- Help answer: which seeding mechanism is more appropriate for AWAKE
  - electron bunch seeding?
  - or ionization front seeding?
- Help understand the transition from SMI to SSM.
- Related to experiments (Run 2a)



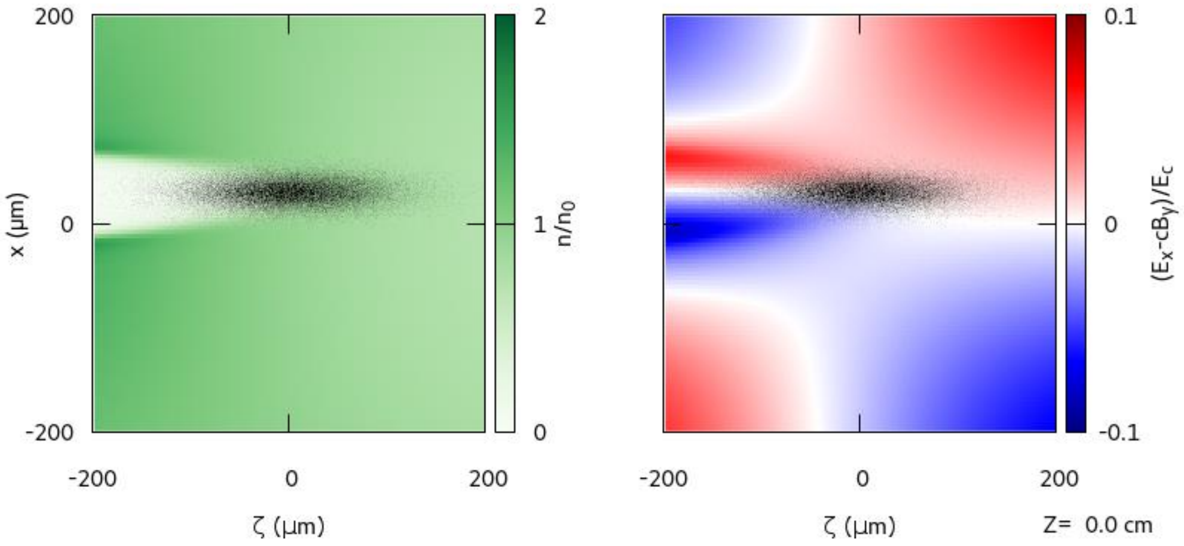


Jitter studies for injection John Farmer

- Jitter in proton beam trajectory occurs during SPS extraction
- Relative misalignment can have serious consequences for the quality of the accelerated witness electron bunch



100 pC charge, 8 μm initial emittance,
0 μm initial offset



100 pC charge, 8 μm initial emittance,
30 μm initial offset

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Jitter studies for injection John Farmer

- Jitter in proton beam trajectory occurs during SPS extraction
- Relative misalignment can have serious consequences for the quality of the accelerated witness electron bunch

100 pC charge, 8 µm initial emittance,
0 µm initial offset

100 pC charge, 8 µm initial emittance,
30 µm initial offset

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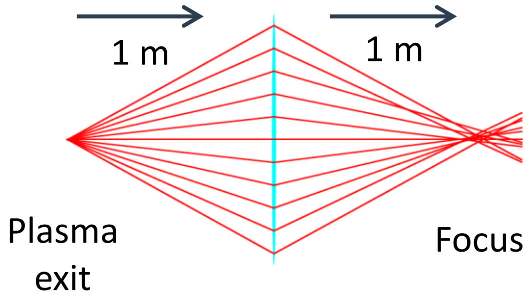
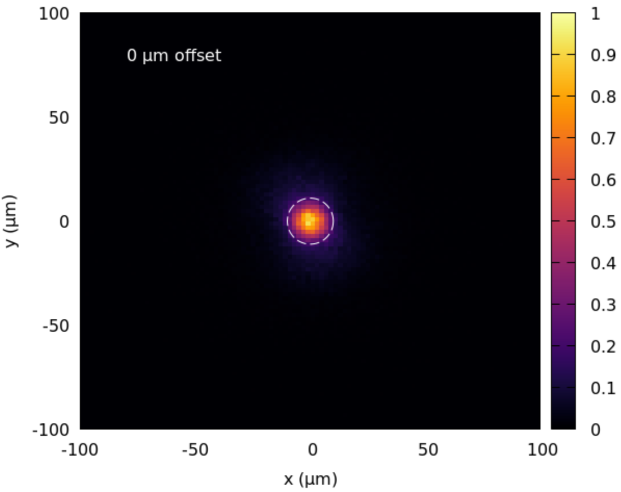
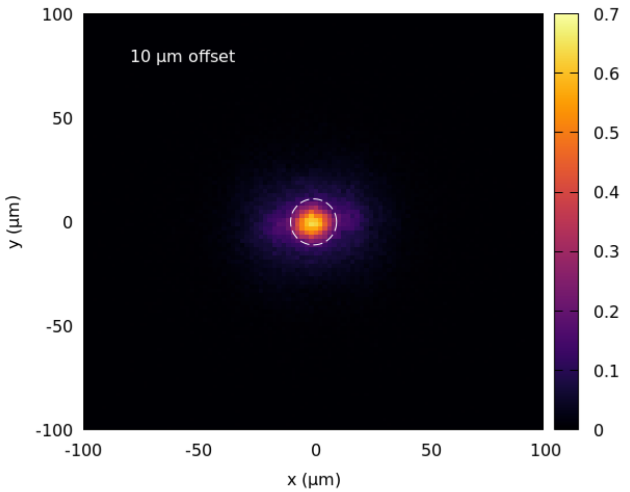
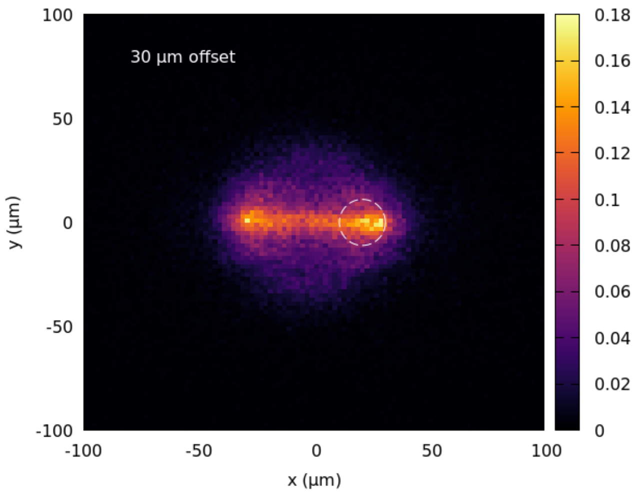
Jitter studies for injection John Farmer

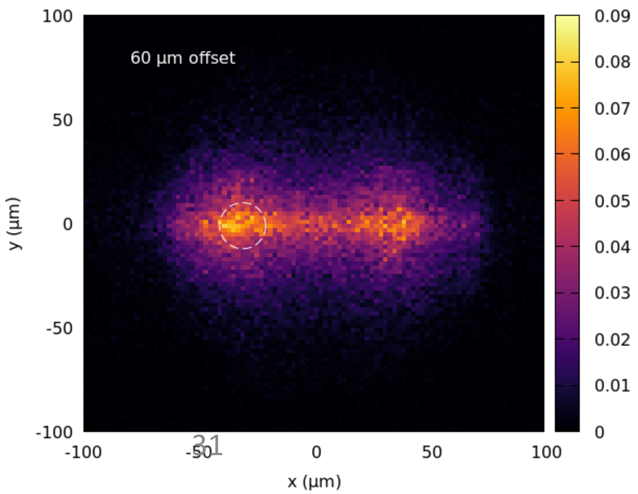
- Impact of Jitter on beam quality evaluated in terms of potential applications e.g. electron-solid target or electro-proton studies







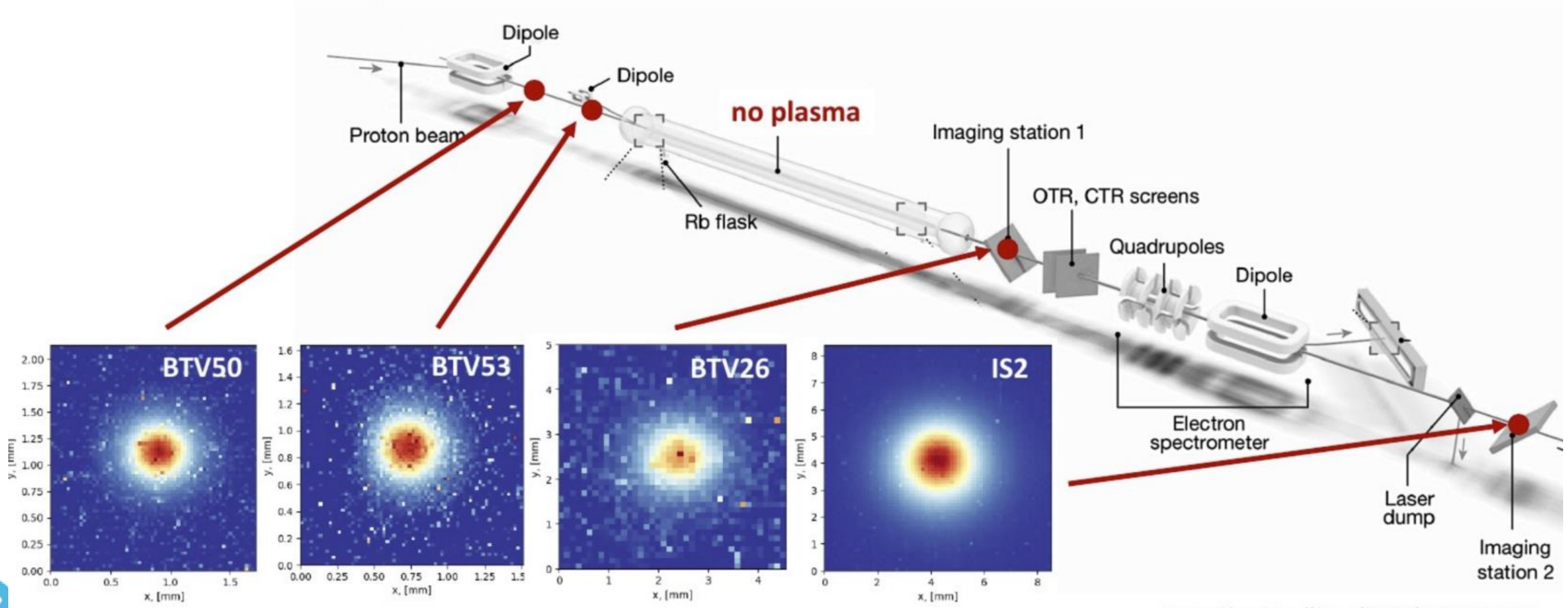




100 pC charge, 8 µm initial emittance

Characterization of the proton beam Vasyl Hafych

1. Development of a proton bunch analysis tool based on fitting the envelope obtained by OTR/scintillator screen on the beam line
2. Development of data acquisition monitor to check saved data and visualize events in the control room



Retrieved from: https://doi.org/10.1038/s41586-018-0485-4

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Conclusion

- Run 2a started with successful data collection providing bases for future publications and PhD thesis
- Run 2a will continue next year to study more in details physics of electron beam seeding of proton bunch modulation and electron acceleration
- Preparation work, design and commission for Run2b are continuing next year
- Studies for Run2c are also ongoing

A big thank to the whole AWAKE collaboration

And thank you for your attention !