Status and Plans for the AWAKE Experiment

Patric Muggli
AWAKE Physics and Experiment Board Chair
Max Planck Institute for Physics
Munich
muggli@mpp.mpg.de
https://www.mpp.mpg.de/~muggli

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

for the
AWAKE Collaboration

COLLABORATION

AWAKE Collaboration, 23 institutes world-wide:

- University of Oslo, Oslo, Norway
- CERN, Geneva, Switzerland
- University of Manchester, Manchester, UK
- Cockcroft Institute, Daresbury, UK
- Lancaster University, Lancaster, UK
- Oxford University, UK
- Max Planck Institute for Physics, Munich, Germany
- Max Planck Institute for Plasma Physics, Greifswald, Germany
- UCL, London, UK
- UNIST, Ulsan, Republic of Korea
- Philipps-Universität Marburg, Marburg, Germany
- Heinrich-Heine-University of Düsseldorf, Düsseldorf, Germany
- University of Liverpool, Liverpool, UK
- ISCTE - Instituto Universitéario de Lisboa, Portugal
- Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia
- Novosibirsk State University, Novosibirsk, Russia
- GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
- TRIUMF, Vancouver, Canada
- Ludwig-Maximilians-Universität, Munich, Germany
- University of Wisconsin, Madison, US
- Uppsala University, Sweden
- Wigner Institute, Budapest
- Swiss Plasma Center group of EPFL, Lausanne, Switzerland

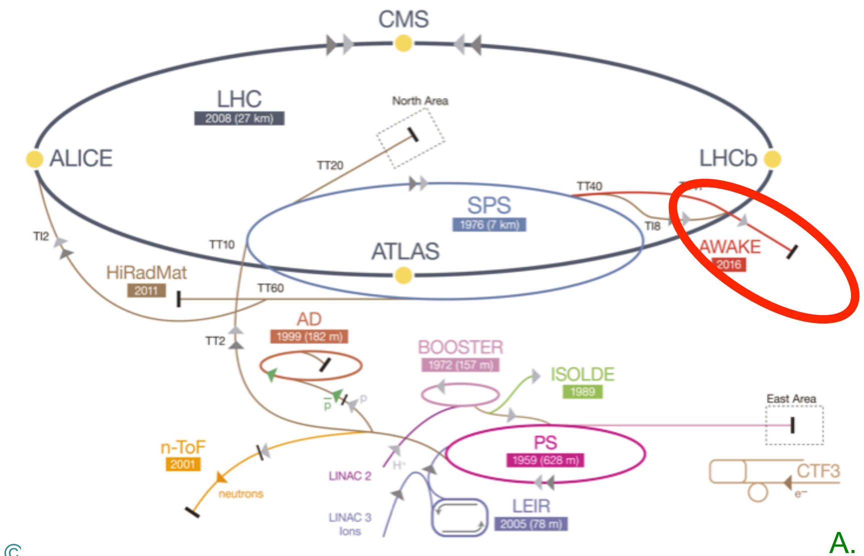
✧Driving wakefields in plasma with a (SPS) proton (p^+) bunch

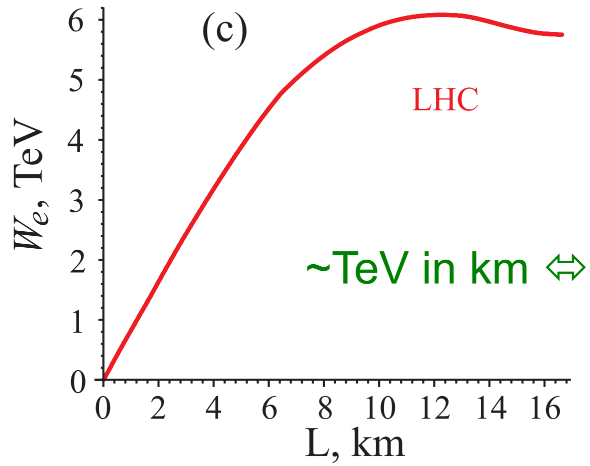
✧Accelerating externally-injected electrons (e^-) to GeV (SPS) to TeV (LHC) energy scale

✧Applications to particle physics experiments:

- ✧Beam dump – solid target experiments
- ✧e^- / p^+ collider (LHC)

A. Caldwell, Eur Phys J C 76, 463 (2016)
M. Wing, Phil Trans A Math Phys Eng Sci., 377(2151) (2019)





~TeV in km ⇔ ~GeV/m

A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)

SUMMARY

- ✧Very successful Run 1
- ✧Clear plan/roadmap toward an accelerator for particle physics applications
- ✧Run 2 has started:
  - ✧First 5 weeks of Run 2a (2021-22) showed e-seeded self-modulation (e-SSM) at low plasma density
  - ✧Run 2b (2023-24), maintaining large accelerating gradient with plasma density step
  - ✧Run 2c (2027-..), external injection of e-bunch, acceleration to multi GeVs, bunch quality
  - ✧Run 2d, scalability of acceleration, development of scalable plasma source
- ✧Application to particle physics following Run 2

AWAKE Run 2 Timeline

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TIME LINE

AWAKE

✧2013: experiment approved

✧2016-18: Run 1, 7 PhDs, 1 Nature, 4 Phys. Rev. Lett. + …

- ✧Self-modulation
- ✧e^- acceleration

✧2021-..: Run 2, e^- bunch for applications at the multi-GeV level

- ✧2021-22: 2a, e^--bunch seeding of self-modulation

- ✧2023-24: 2b, new plasma source with density step to maintain high amplitude of wakefields
- ✧2027-…: 2c, external e^--bunch bunch injection and acceleration, multi-GeV
- ✧2019-…: 2d, development of scalable plasma source(s), scaling of energy gain

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TiME LiNE

AWAKE

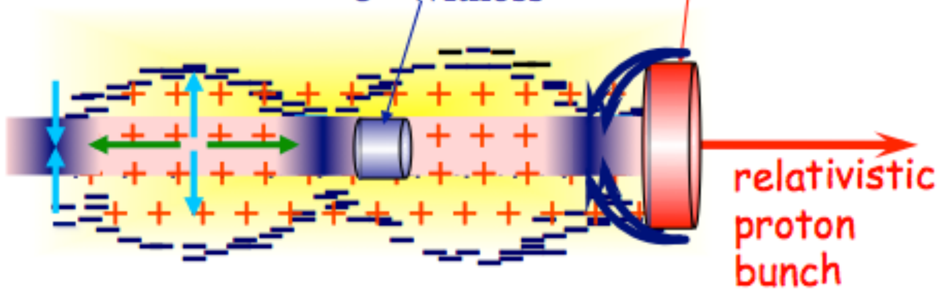
✧https://twiki.cern.ch/twiki/bin/view/AWAKE/AwakePublic

AWAKE Collaboration Papers

Authors	Title	Journal	Year	DOI/arXiv
V. Hafych, et al. (AWAKE Collaboration)	Analysis of Proton Bunch Parameters in the AWAKE Experiment		2021	2109.12893
S. Gessner, et al. (AWAKE Collaboration)	Evolution of a plasma column measured through modulation of a high-energy proton beam		2020	2006.09991
P.I. Morales Guzman, et al. (AWAKE Collaboration)	Simulation and experimental study of proton bunch self-modulation in plasma with linear density gradients	PRAB	2021	DOI
F. Batsch, et al. (AWAKE Collaboration)	Transition between Instability and Seeded Self-Modulation of a Relativistic Particle Bunch in Plasma	PRL	2021	DOI
J. Chappell, et al. (AWAKE Collaboration)	Experimental study of extended timescale dynamics of a plasma wakefield driven by a self-modulated proton bunch	PRAB	2021	DOI
F. Braunmüller, et al. (AWAKE Collaboration)	Proton Bunch Self-Modulation in Plasma with Density Gradient	PRL	2020	DOI
A. A. Gorn, et al. (AWAKE Collaboration)	Proton beam defocusing in AWAKE: comparison of simulations and measurements	PPCF	2020	DOI
M. Turner, et al. (AWAKE Collaboration)	Experimental study of wakefields driven by a self-modulating proton bunch in plasma	PRAB	2020	DOI
E. Gschwendtner, et al. (AWAKE Collaboration)	Proton-driven plasma wakefield acceleration in AWAKE	PTRSA	2019	DOI, Correction
M. Turner, et al. (AWAKE Collaboration)	Experimental Observation of Plasma Wakefield Growth Driven by the Seeded Self-Modulation of a Proton Bunch	PRL	2019	DOI
AWAKE Collaboration	Experimental Observation of Proton Bunch Modulation in a Plasma at Varying Plasma Densities	PRL	2019	DOI
AWAKE Collaboration	Acceleration of electrons in the plasma wakefield of a proton bunch	Nature	2018	DOI

… + shorter author list publications

PLASMA WAKEFIELDS (p^+)



✧Plasma: initially (globally) neutral: $n_e=n_i$

✧Scaling:

$$\omega_{pe} = \left(\frac{n_e e^2}{\varepsilon_0 m_e}\right)^{1/2} \propto n_e^{1/2}$$ Plasma angular frequency

$$E_{WB} = \frac{m_e c \omega_{pe}}{e} \propto n_e^{1/2}$$ Cold plasma wave breaking field
Maximum accelerating field

$$E_{WB} \cong 100\sqrt{n_e(cm^{-3})} = 1GV/m \; @ \; n_e = 10^{14} cm^{-3}$$ (f_{pe}~100GHz)

Scaling favors
short, tight bunch
in high-density plasma

$$\sigma_r, \sigma_z \leq c/\omega_{pe} \propto n_e^{-1/2}$$ Bunch fits in a (plasma skin depth)³ $c/\omega_{pe} = 531\mu m \; @ \; n_e = 10^{14} cm^{-3}$

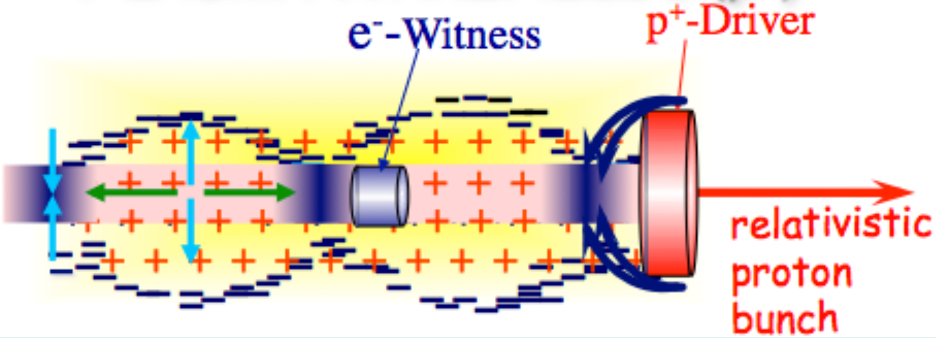
✧SPS p^+ bunch:

σ_z=10cm
σ_r=200µm = c/ω_{pe}=> n_e=7x10^{14}cm^{-3}
E_{WB}=2.5GV/m

} σ_z>>c/ω_{pe}

⇒Self-modulation process
⇒$\lambda_{pe}=2\pi c/\omega_{pe}$~1mm

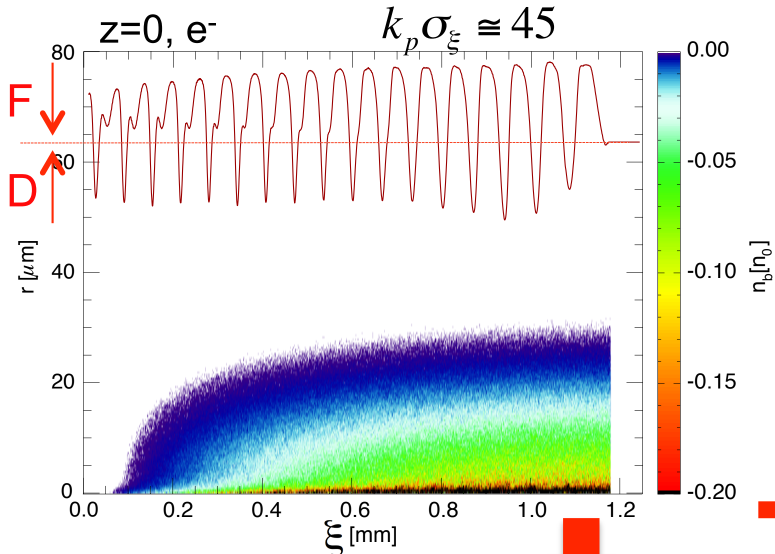
PLASMA WAKEFIELDS (p^+)

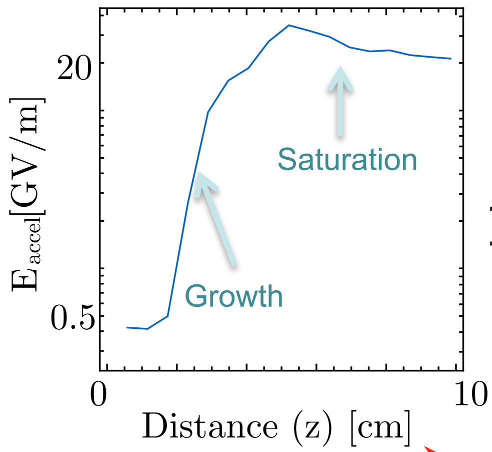


- ✧ Why p^+?
- ✧ p^+ bunches carry large amounts of energy per particle (400GeV SPS, 6.5TeV LHC) and per bunch (19, 120kJ)
- ✧ Short e^- bunches (PWFA), laser pulses (LWFA) <100J
- ✧ p^+ bunch drives wakefields over long plasma length
- ✧ Acceleration in a single plasma, avoid staging to reach high e^- energies (TeV)
- ✧ ns-long p^+ bunch needs self-modulation to drive GV/m accelerating (wake)fields

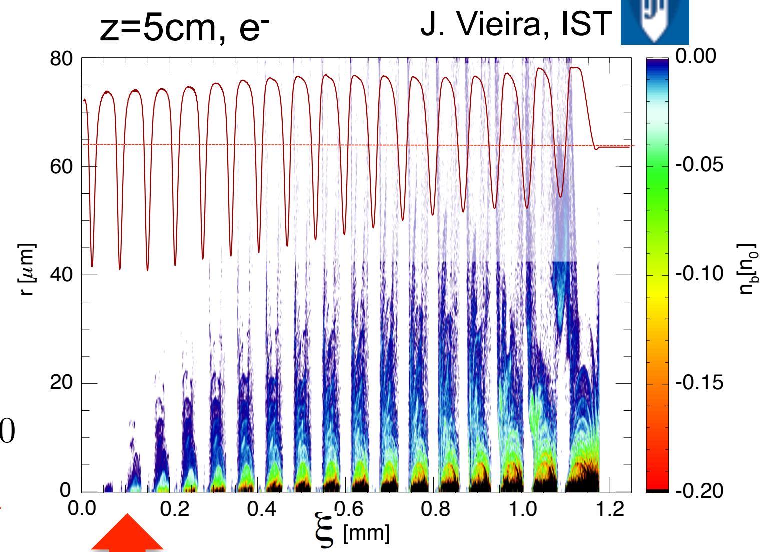
SEEDED SELF-MODULATiON (SSM)

Kumar, Phys. Rev. Lett. 104, 255003 (2010)



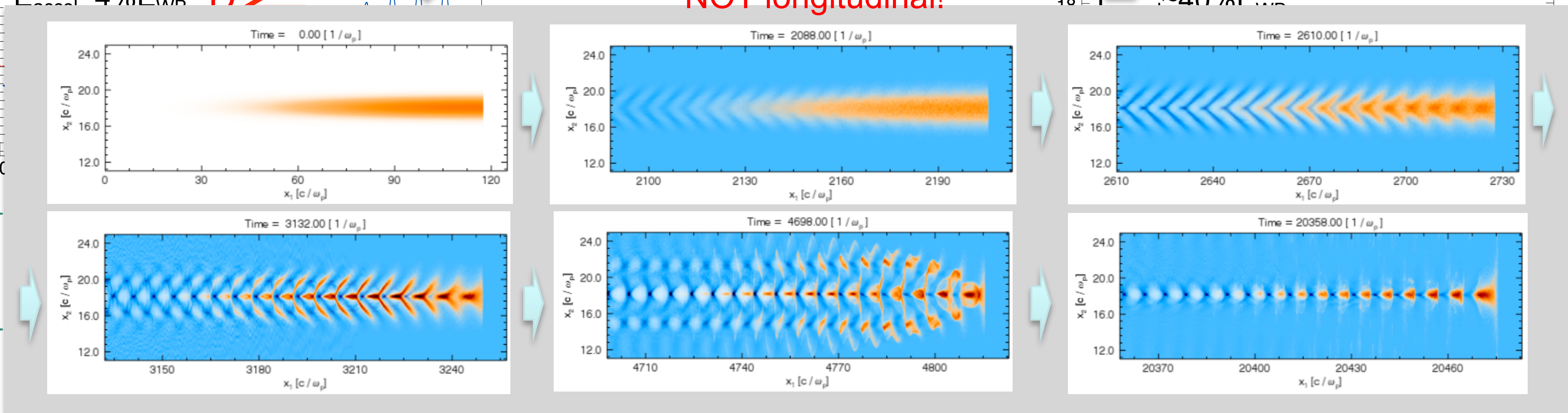


J. Vieira, IST



Transverse

NOT longitudinal!



(011)

(2011)

J. Vieira et al., Phys. Plasmas 19, 063105 (2012)

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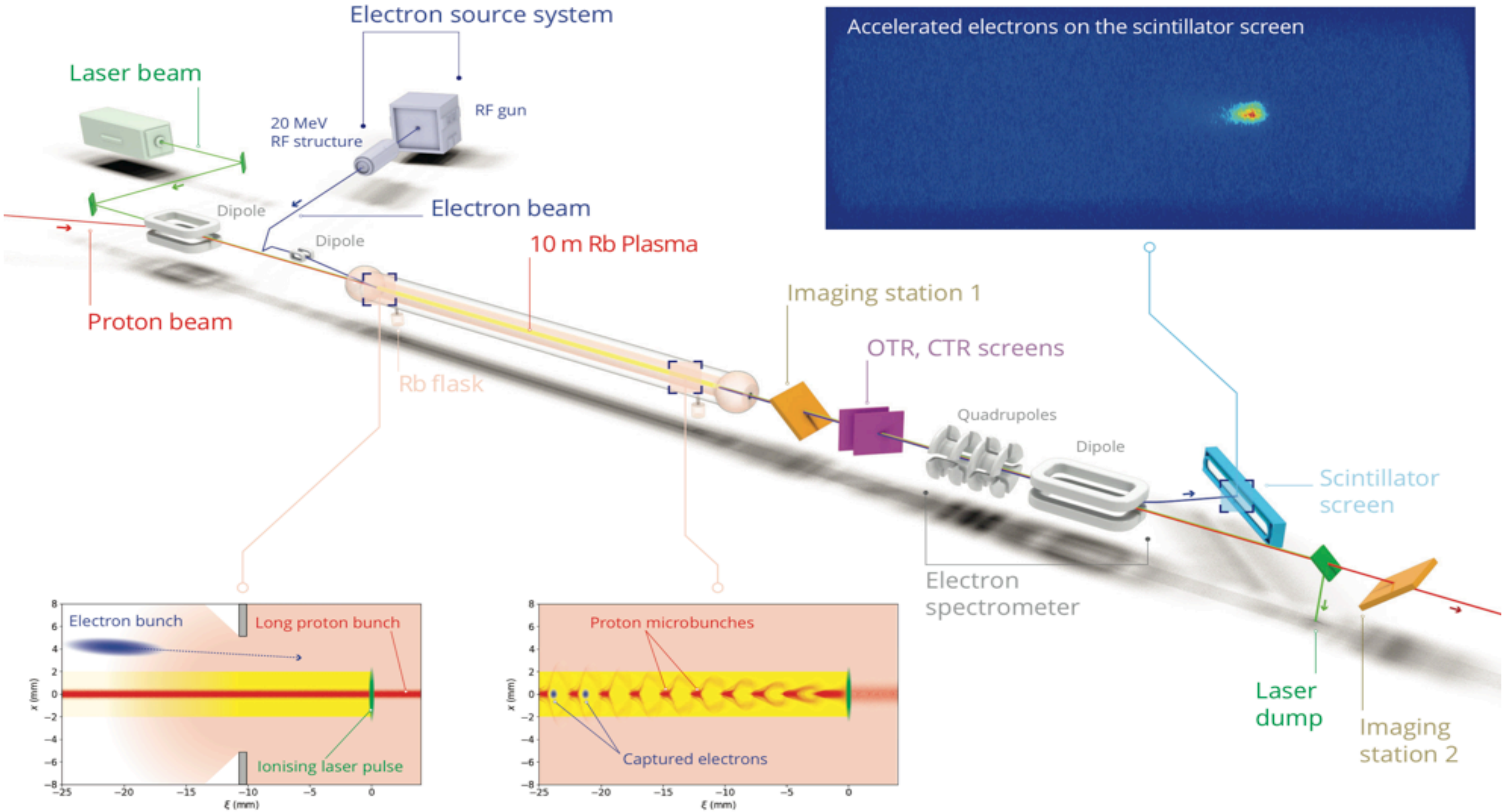
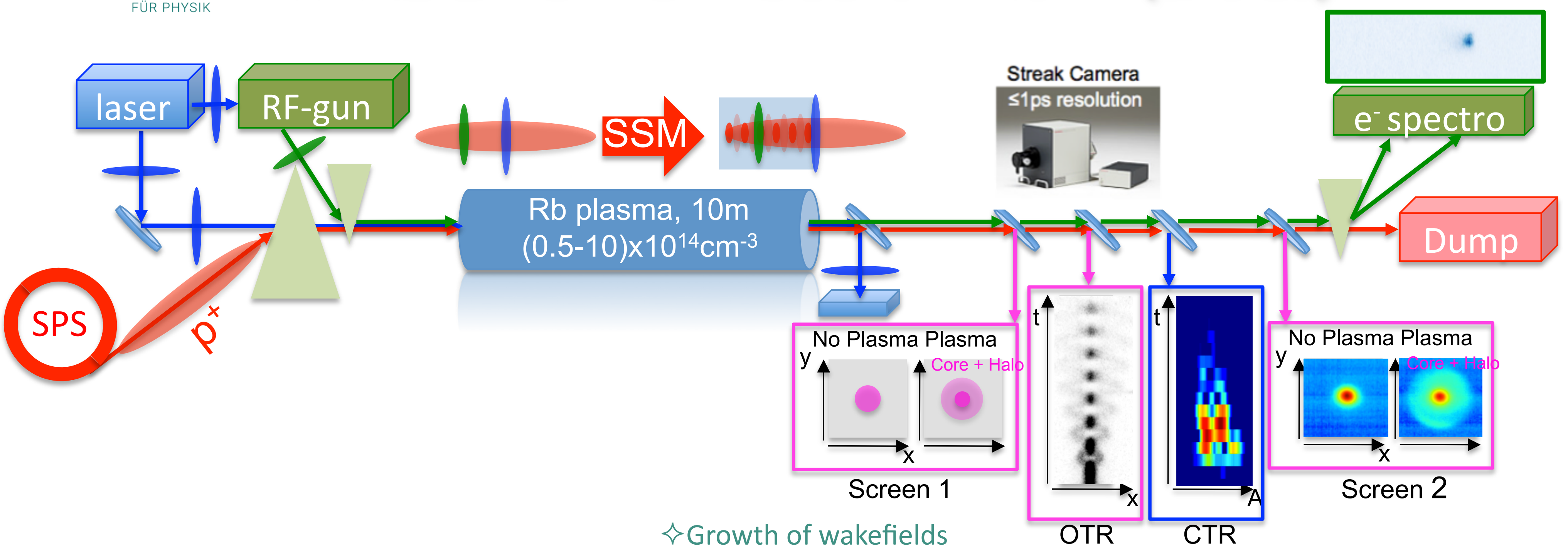
AWAKE EXPERiMENTAL SETUP - RUN 1 (and 2a)

AWAKE

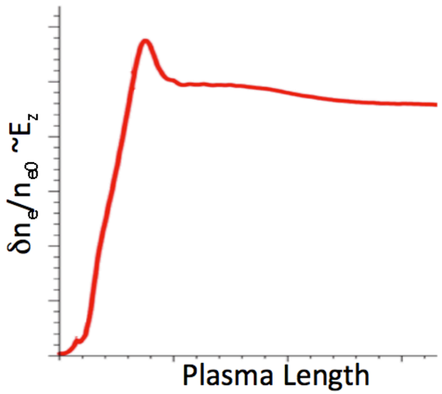


AWAKE, Nature 561, 363 (2018)

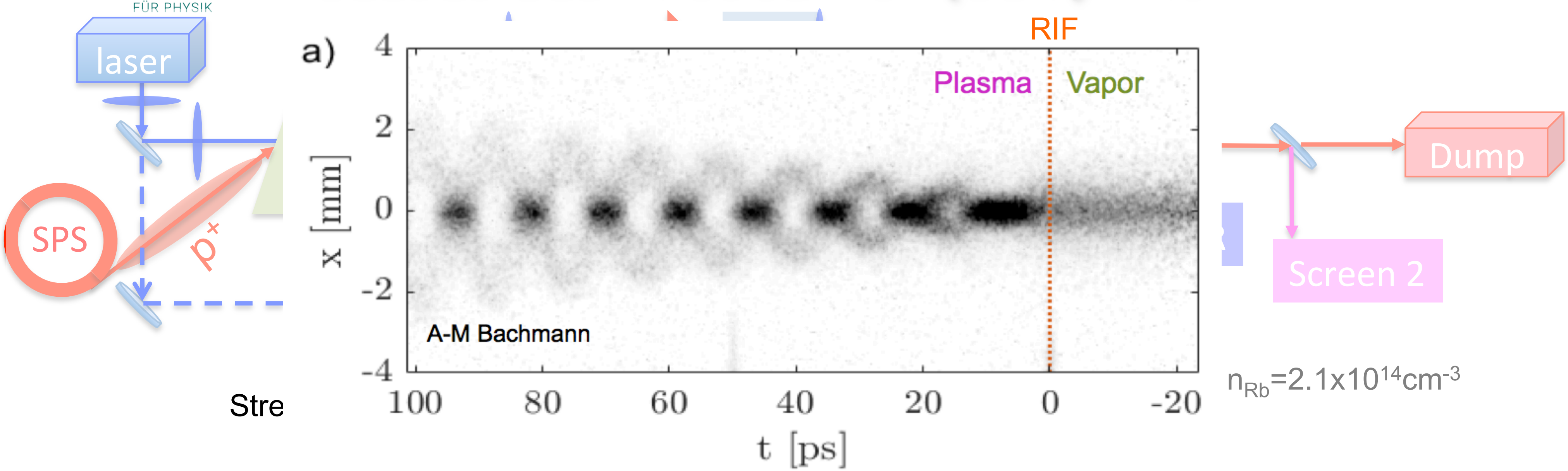
AWAKE EXPERIMENTAL SETUP - RUN 1 (and 2a)

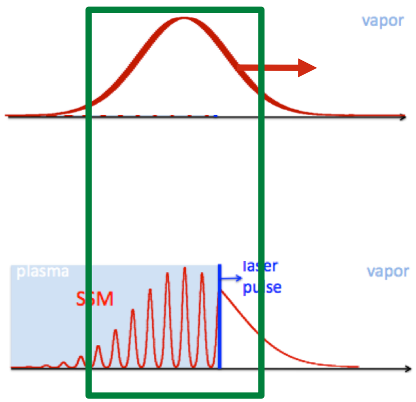


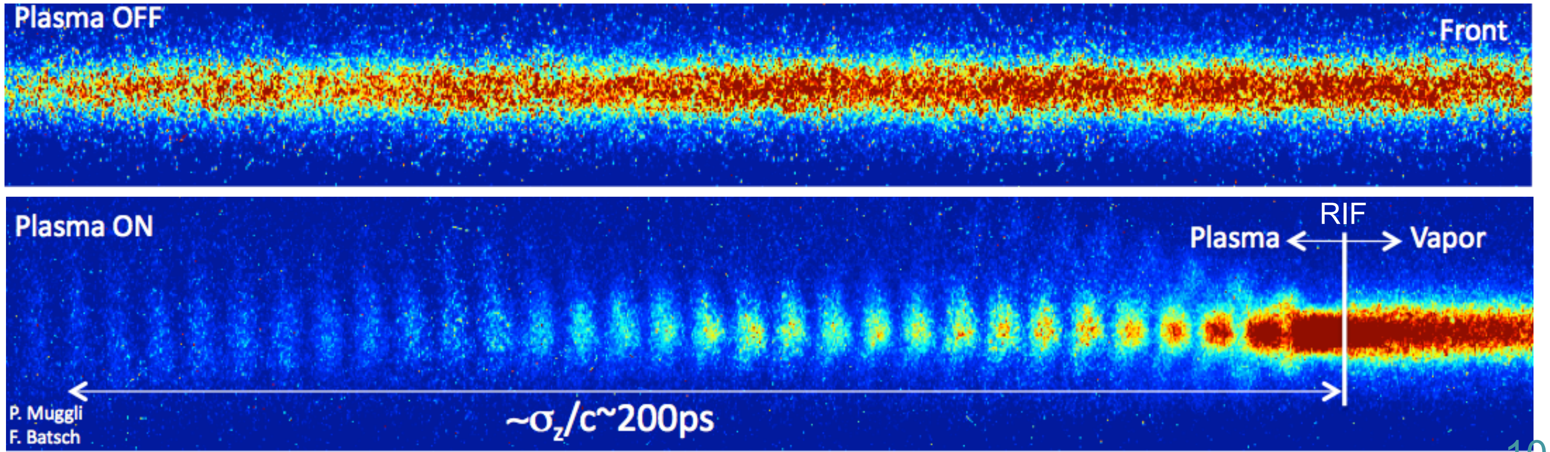
✧Growth of wakefields



SEEDED SELF-MODULATiON (SSM) - RUN 1

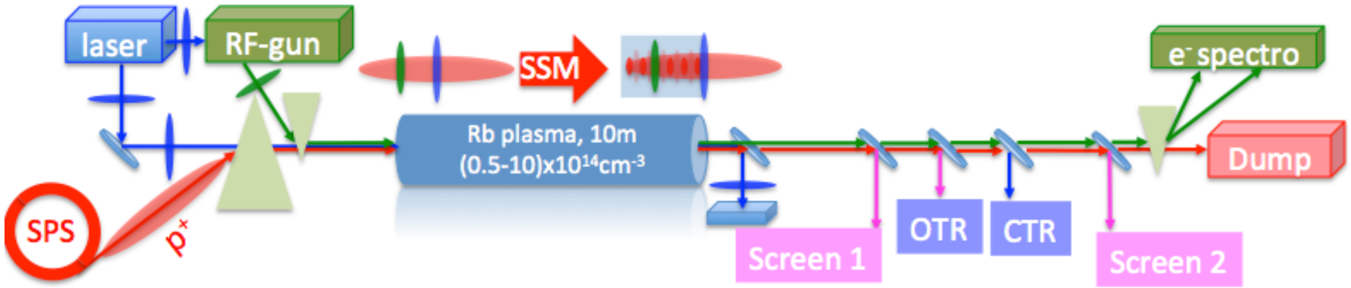


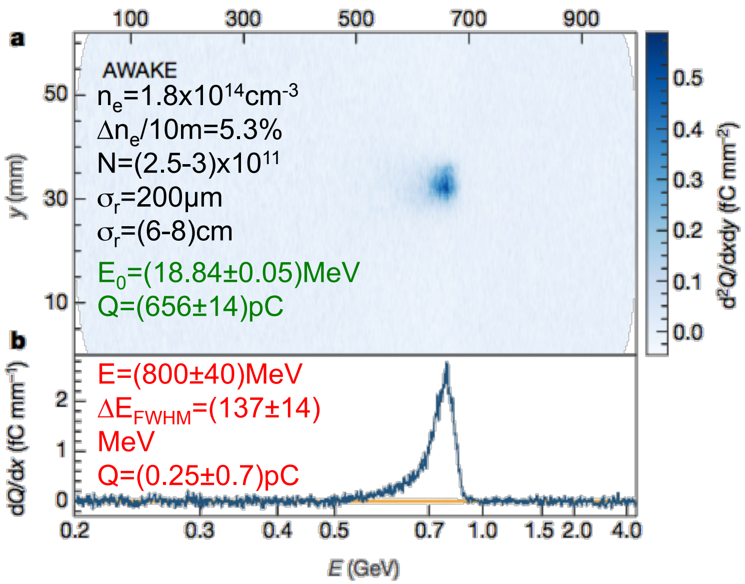


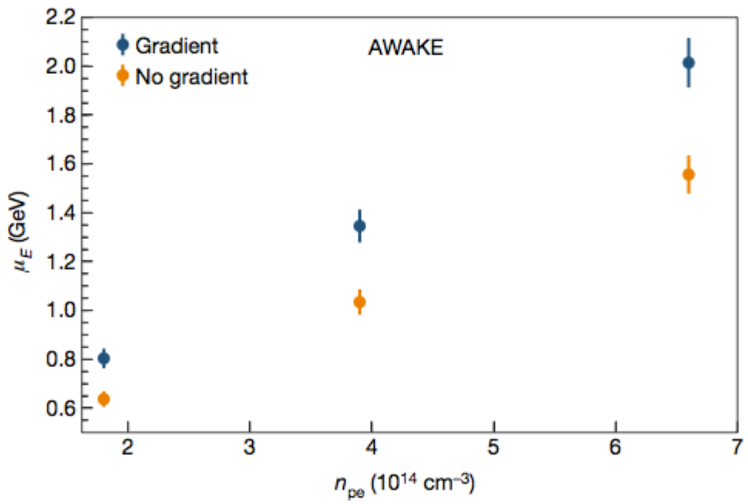


 AWAKE, Phys. Rev. Lett. 122, 054802 (2019) M. Turner et al., Phys. Rev. Lett. 122, 054801 (2019)

ACCELERATiON EXTERNALY-INJECTED e⁻ - RUN 1



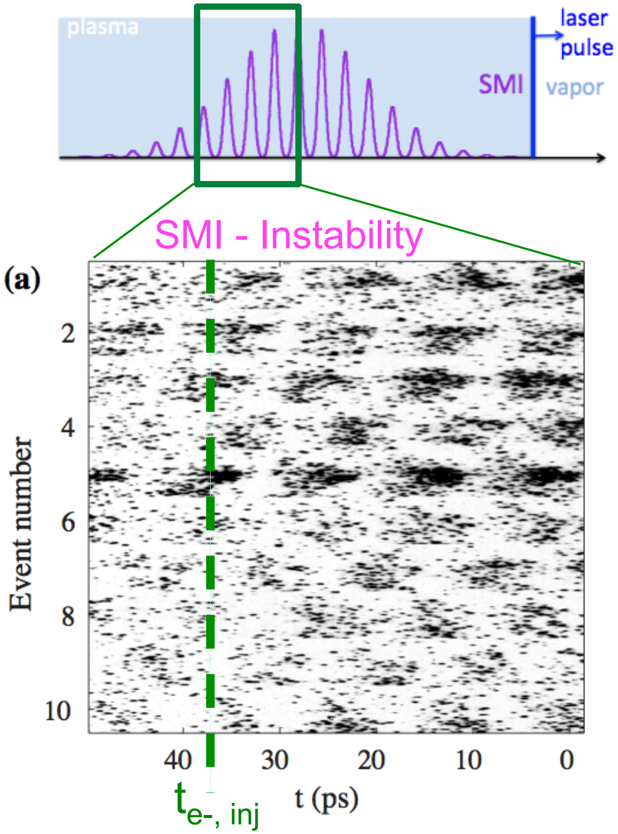




- ✧ Injection at an angle (~1-3mrad)
- ✧ Finite ΔE/E
- ✧ Up to 2GeV energy gain (from ~19MeV)
- ✧ Captured charge: ~pC

AWAKE, Nature 561, 363 (2018)

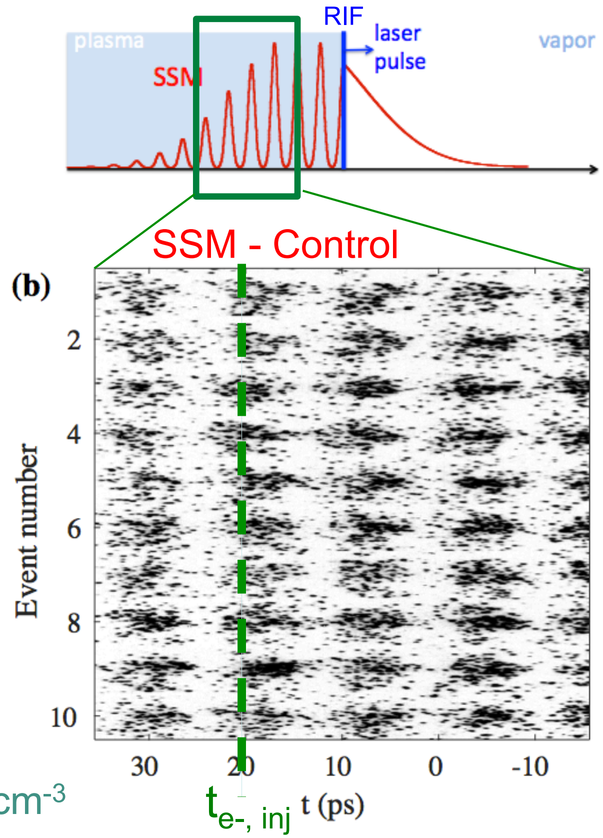
SEEDED SELF-MODULATION (SSM) - RUN 1

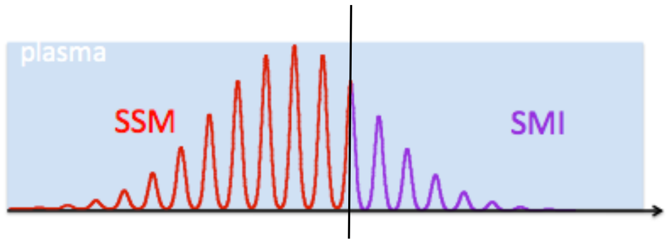


Relativistic Ionization Front
(RIF)
Seeding

µ-bunches
@ varying times

µ-bunches
@ fixed times





SMI –SSM transition:

✧t_{RIF}~$2\sigma_{p+}$

✧2.8MV/m ≤ $E_{z,seed}$ ≤4MV/m @ $n_e=10^{14}cm^{-3}$

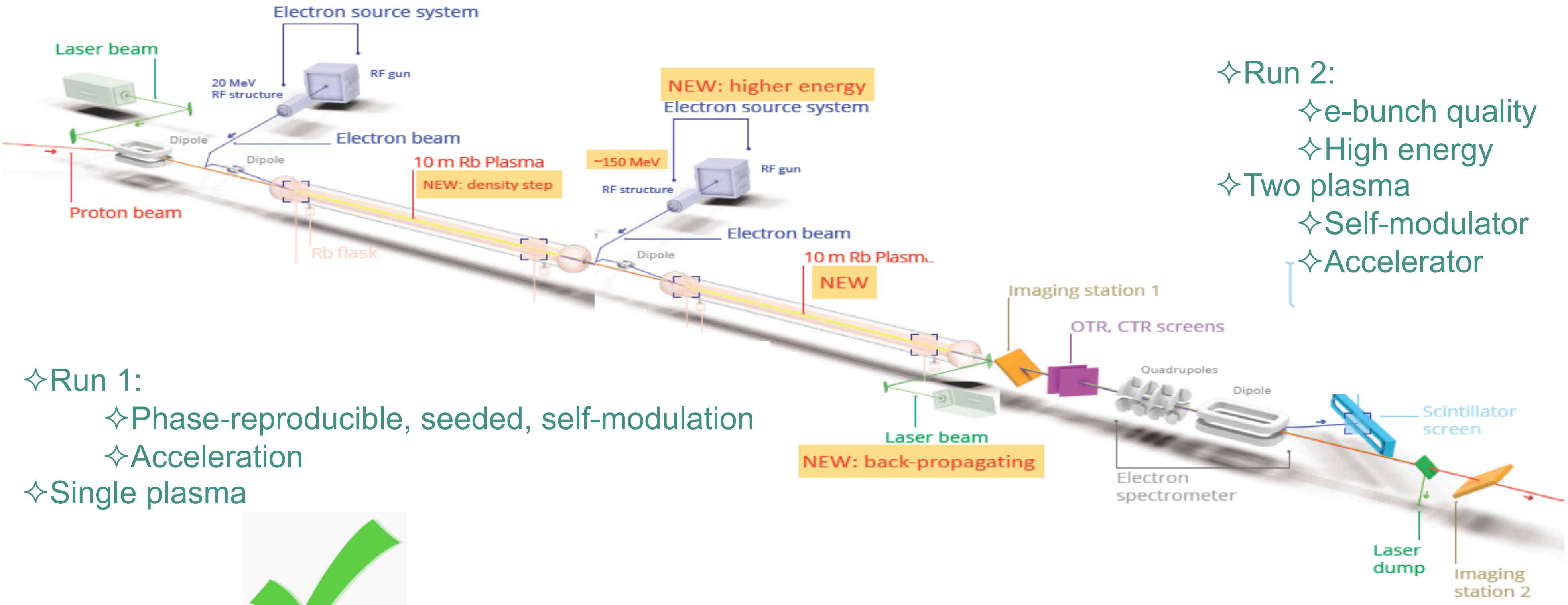
✧Transition from SMI to SSM

✧SSM, RIF seeding: $\Delta\Phi/2\pi\leq 8\%$

✧Essential for deterministic external injection of a e^- bunch in the *accelerating* and *focusing* phase of the wakefields

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

Run 2



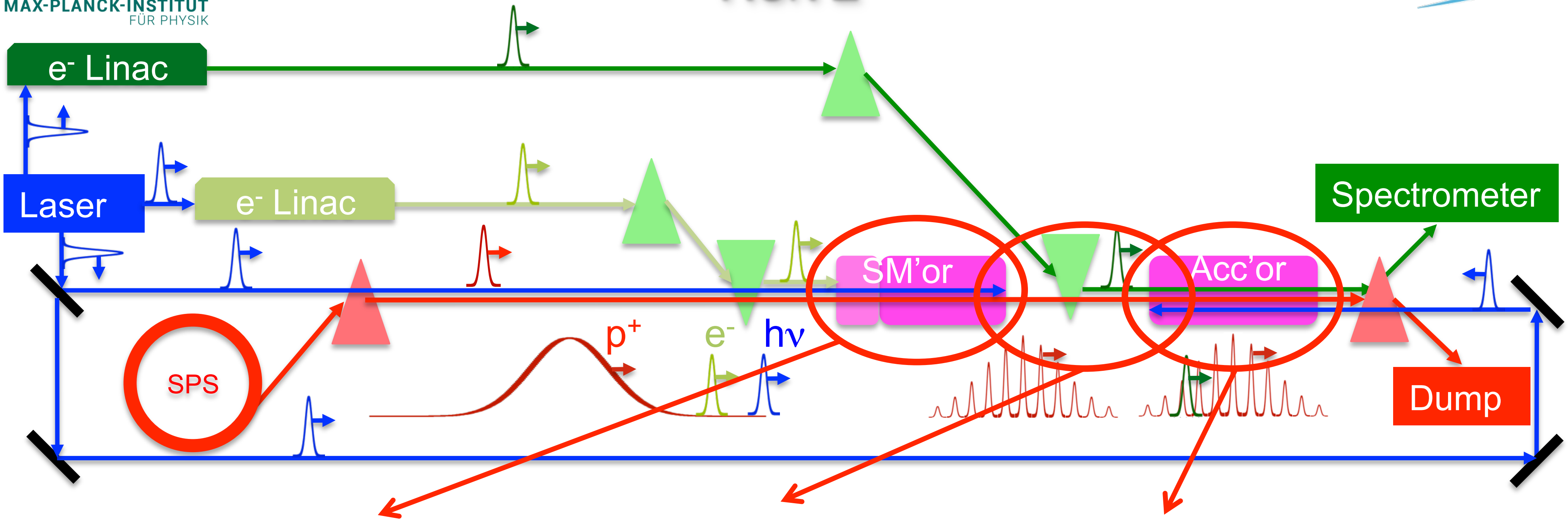
✧Run 2:
- ✧e-bunch quality
- ✧High energy

✧Two plasma
- ✧Self-modulator
- ✧Accelerator

✧Run 1:
- ✧Phase-reproducible, seeded, self-modulation
- ✧Acceleration

✧Single plasma

Run 2

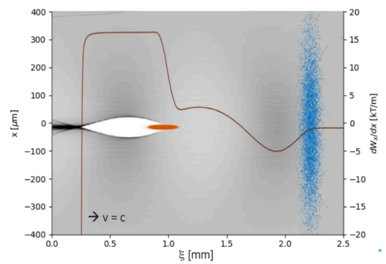


<u>Self-Modulator, Run 2a,b:</u>
✧e^- bunch seeding
✧Plasma density step

<u>e^- external injection, Runs 2 c,d:</u>
✧On-axis injection
✧Bunch quality
✧Plasma source for >>GeV scale

<u>Accelerator:</u>
✧Blow-out
✧Beam loading
✧Beam matching

✧Bunch quality

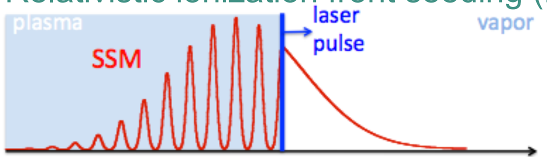


V. K. Berglyd Olsen, PR- AB 21, 011301 (2018)

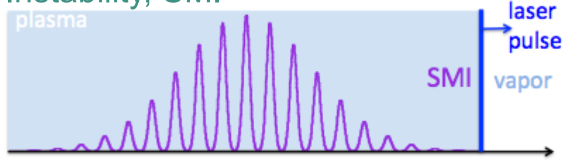
e⁻-Bunch Seeded Self-Modulation (eSSM)

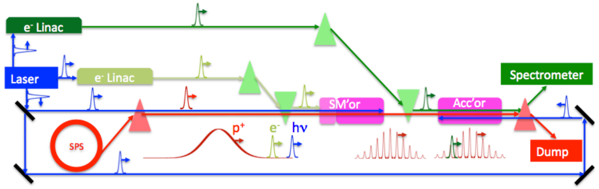
Run 1: single, laser-ionized plasma, relativistic ionization

Relativistic ionization front seeding (RIF), SSM



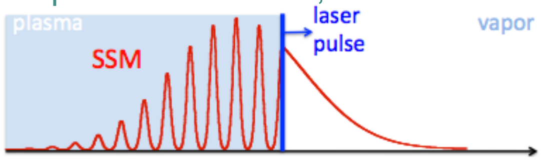
Instability, SMI



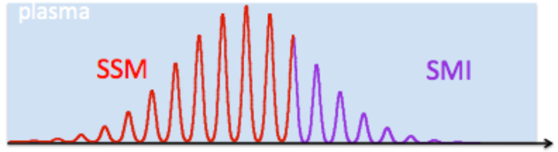


Run 2 issue: two plasmas

1st plasma: RIF SSM, self-modulator



2nd plasma : preformed plasma, accelerator

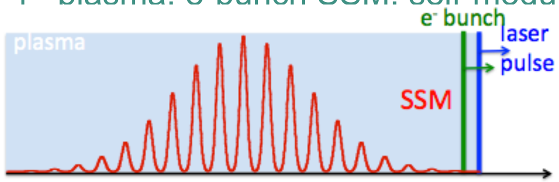


Interference:

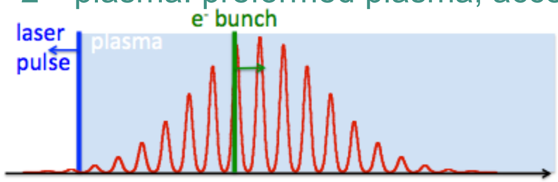
front SSM – back SMI?

Run 2 solution: e-bunch seeding

1st plasma: e-bunch SSM, self-modulator



2nd plasma: preformed plasma, accelerator



✧Whole bunch self-modulated

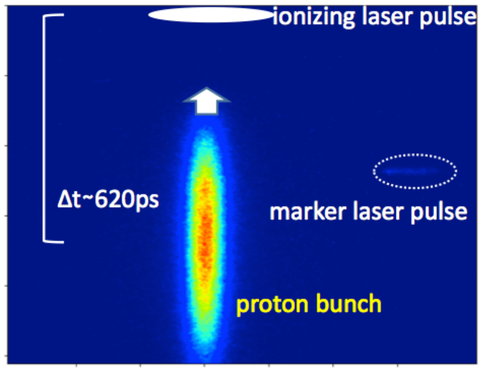
✧No SMI

✧No seed, preformed plasma => SMI (phase not reproducible)
✧e-bunch seed (eSSM) => reproducible phase => entire bunch self-modulated

e⁻-BUNCH SEEDED SELF-MODULATION (eSSM)

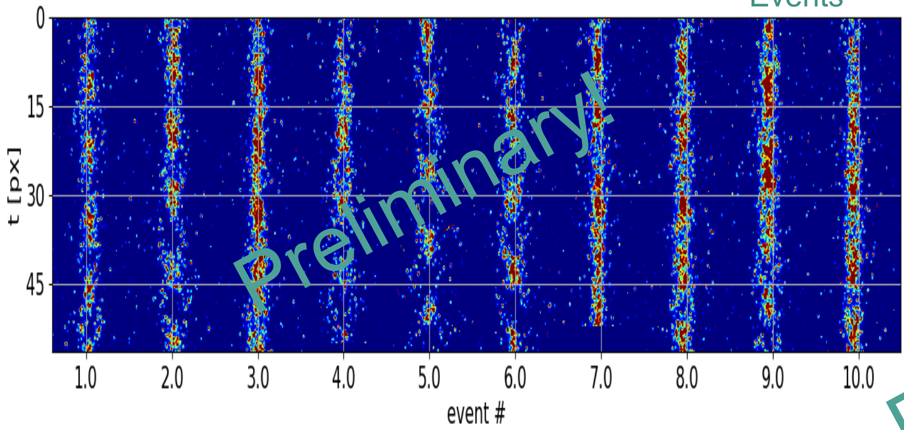
Preliminary!

No seed – pre-formed plasma



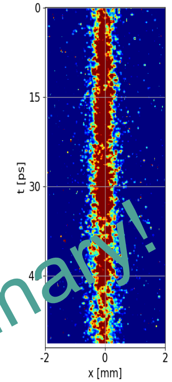
NO Seeding

Individual Events



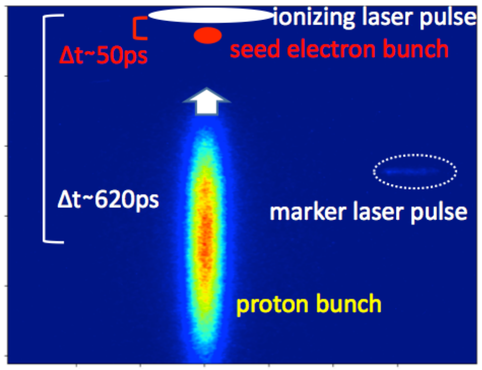
SMI

Sum of Events

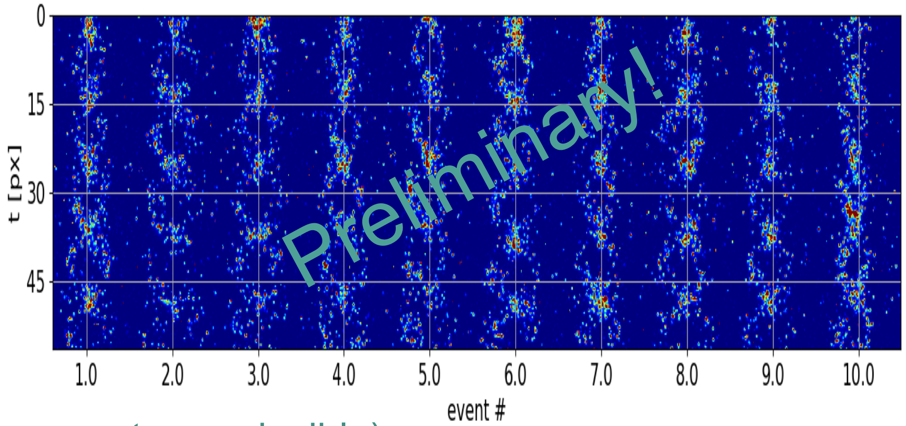


Preliminary!

e-bunch seed

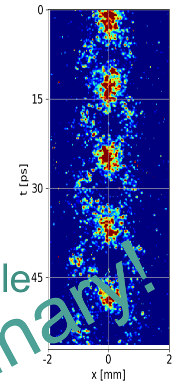


e-bunch Seeding



eSSM

Reproducible Phase



Preliminary!

L. Verra

- ✧No seed, preformed plasma => SMI (phase not reproducible)
- ✧e-bunch seed, => reproducible phase => eSSM => entire bunch self-modulated
- ✧RMS phase variation ~8% of 2π, similar to RIF-SSM, measurement dominated

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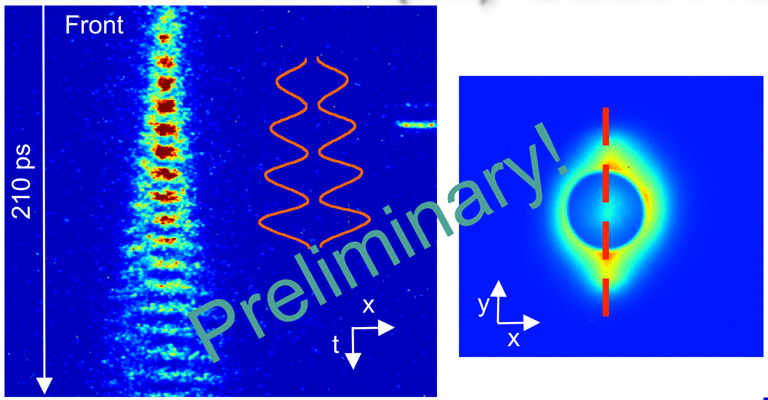
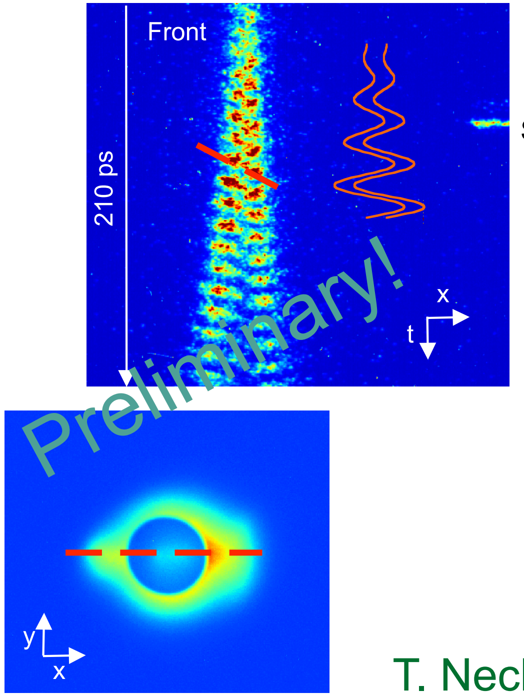
HOSiNG INSTABiliTY (HI) SEEDiNG

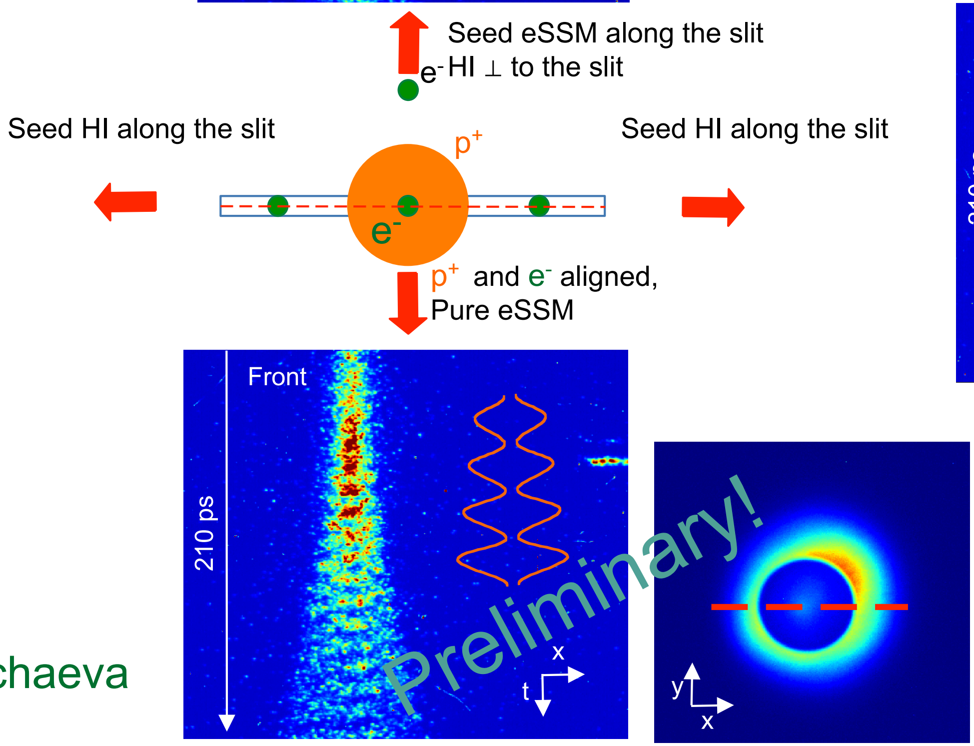
AWAKE

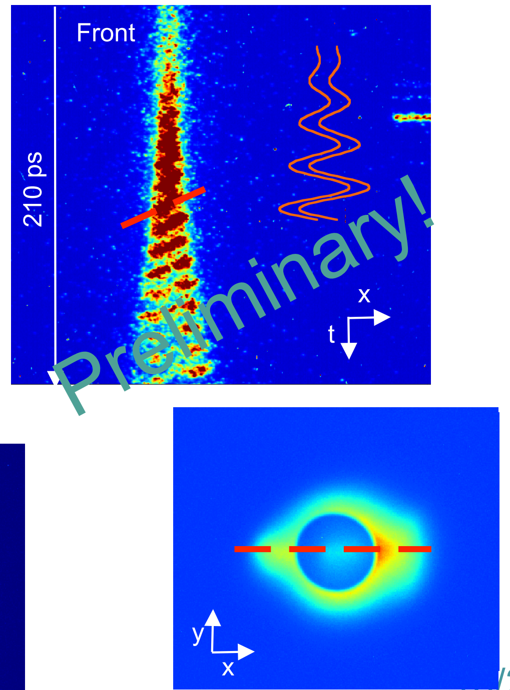
- Hosing Instability seeded by misaligning e- bunch (eSSM)
- eSSM in one plane
- eHI in the other



Preliminary!







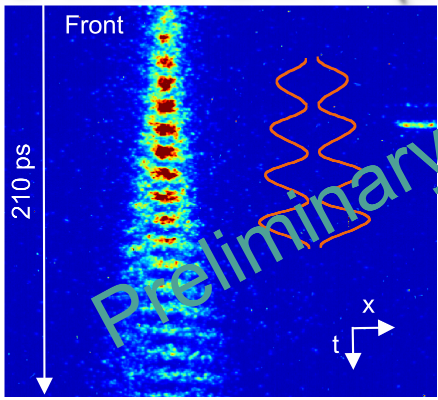
T. Nechaeva

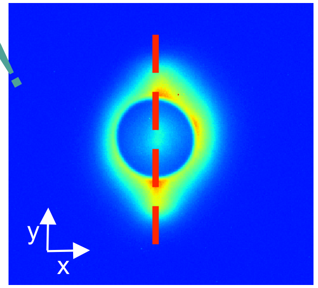
HOSiNG INSTABiliTY (HI) SEEDiNG

MAX-PLANCK-INSTITUT FÜR PHYSIK

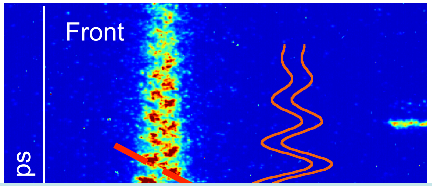
AWAKE

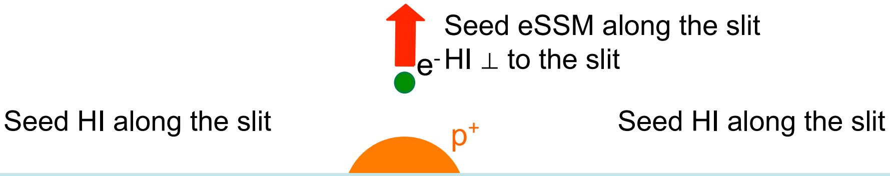
- ✧ Hosing Instability seeded by misaligning e- bunch (eSSM)
- ✧ eSSM in one plane
- ✧ eHI in the other

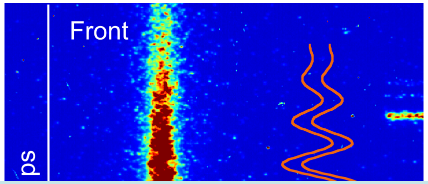




Preliminary!

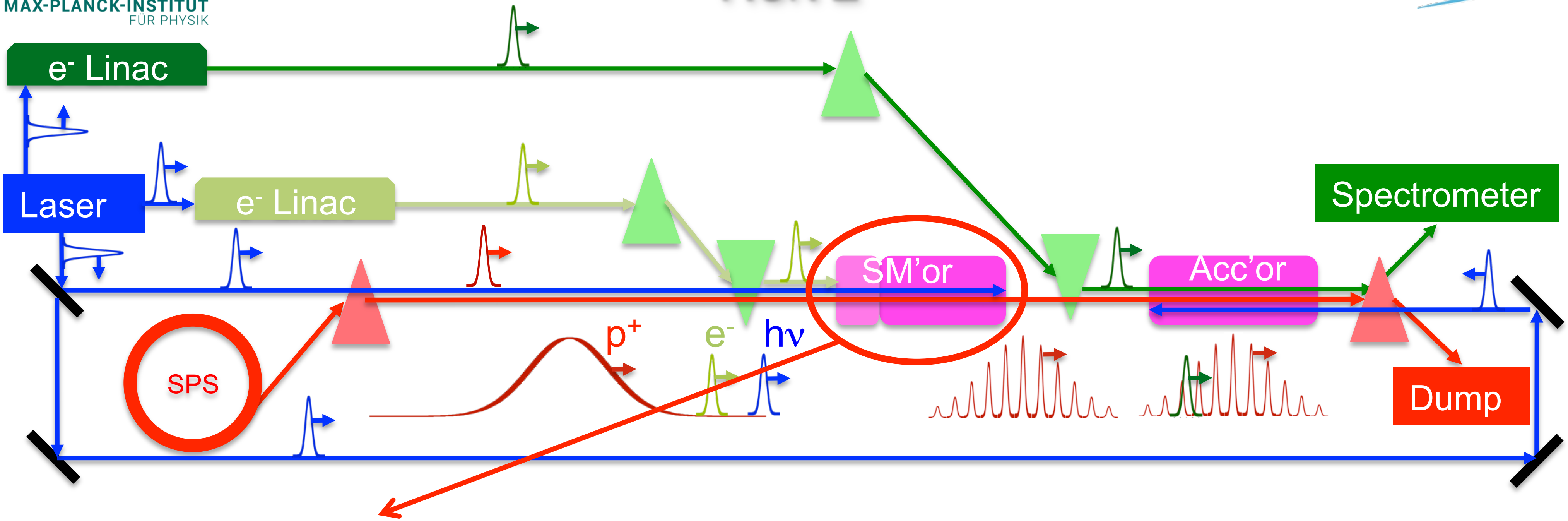






- ✧ Hosing Instability
  - ✧ May compete with self-modulation
  - ✧ May grow over very long distance in plasma
- ✧ Important to study!

RUN 2



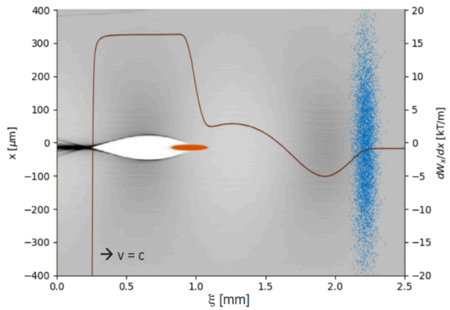
<u>Self-Modulator, Run 2a,b:</u>

✧e^- bunch seeding

✧Plasma density step

<u>e^- external injection, Runs 2 c,d:</u>

✧On-axis injection



V. K. Berglyd Olsen, PR- AB 21, 011301 (2018)

<u>Accelerator:</u>

✧Blow-out

✧Beam loading

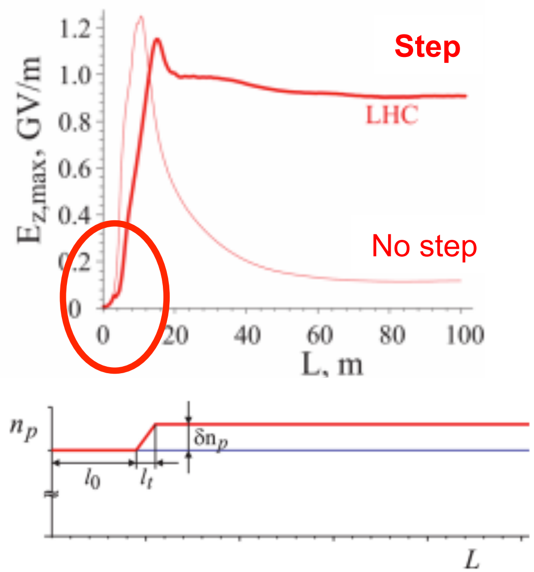
✧Beam matching

✧Plasma source for >>GeV scale

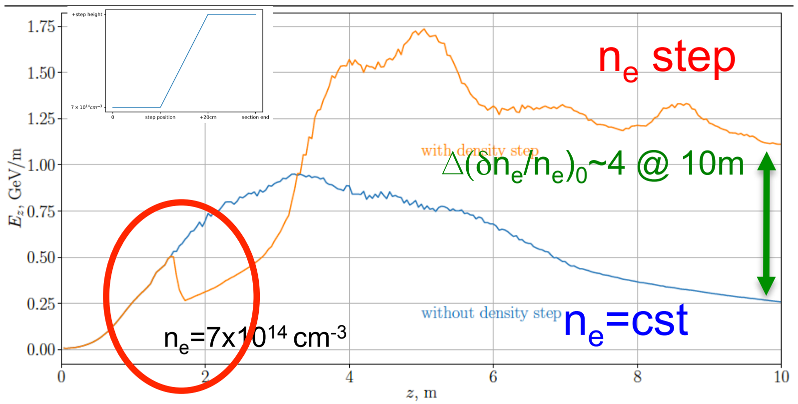
RUN 2b PREPARATION

✧ Plasma density step for wakefields to maintain large amplitude after saturation of SM

Calwell, POP 18, 103101 (2011)

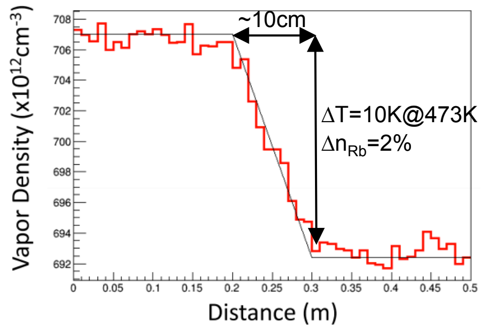


K. Lotov V. Minakov, private communication



✧Predicted effect $\Delta n_{Rb}(/\Delta T)$, molecular flow simulation

G. Plyushchev , J. Phys. D: 51(2), 025203 (2017)



✧ Impose temperature step ΔT

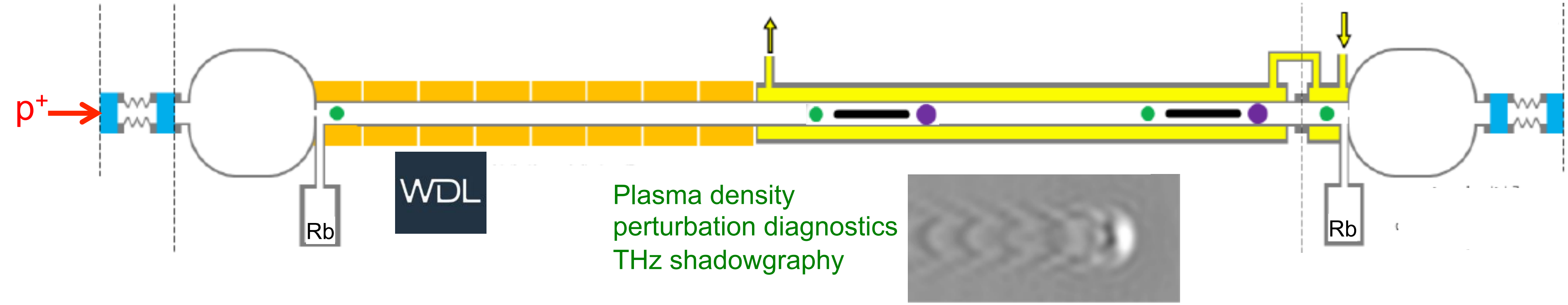
✧ Rb vapor density step: Δn_{Rb}~ΔT, 0-10% @500K

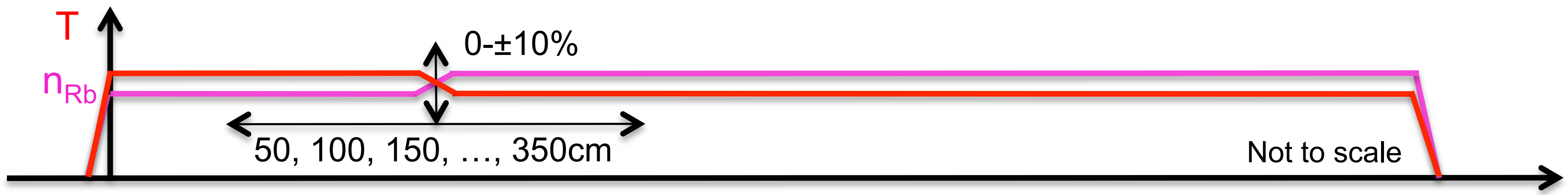
✧ Laser ionization $\Delta n_e = \Delta n_{Rb}$~ΔT

✧ New vapor source and new diagnostic for wakefields

Run 2b Preparation

- ✧ New vapor source: temperature step
- ✧ Short electrical heaters + fluid heat exchanger

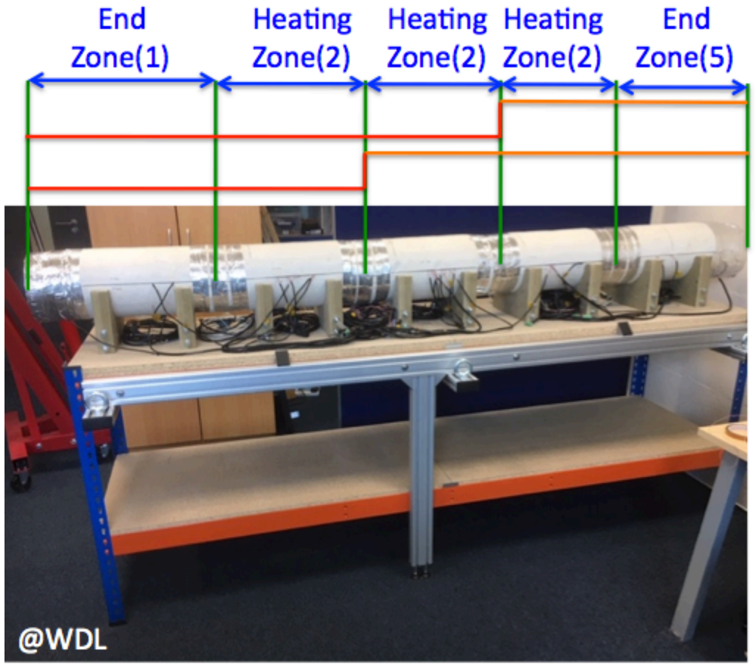


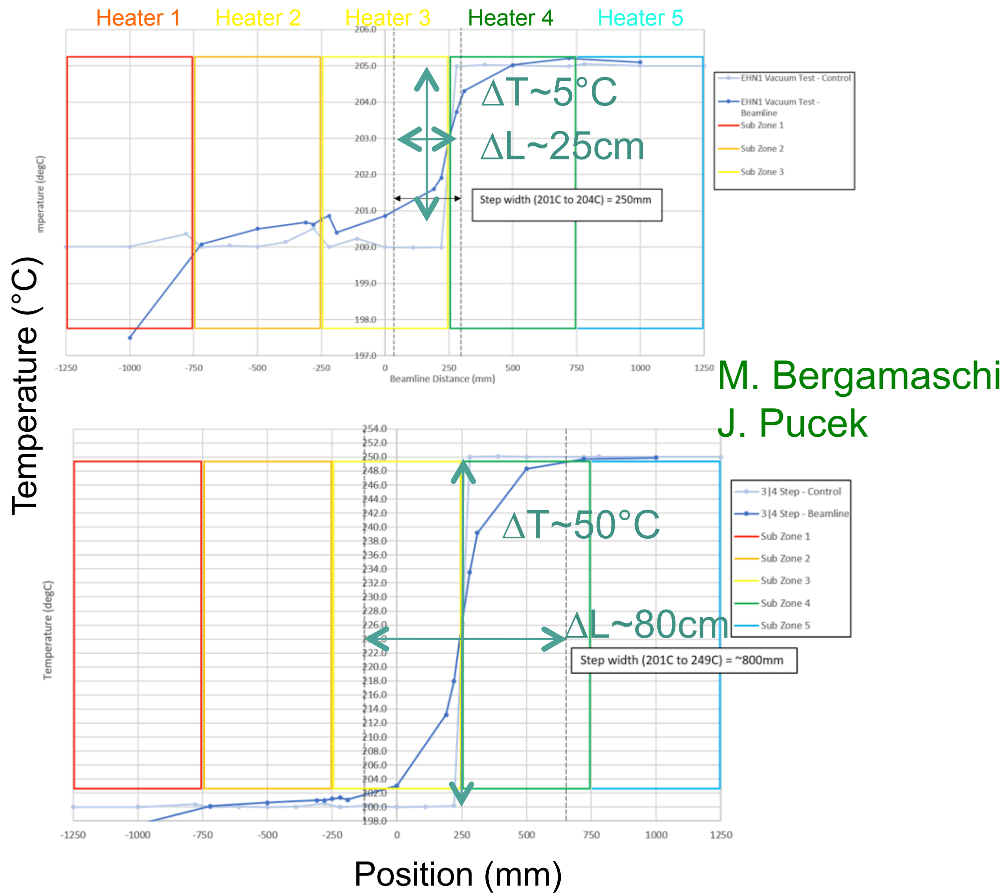


- ✧ Impose temperature step ΔT
- ✧ Test simulation predictions
- ✧ Source for Run 2b = self-modulator source of Run 2c

RUN 2b PREPARATION

✧ New vapor source prototype: temperature step prototype (EHN1)





M. Bergamaschi
J. Pucek

✧ Impose temperature step 0≤ΔT≤50K or 0-10%@500K
✧ Step width ΔL increases with ΔT
✧ Effect of step on wakefields weakly dependent on step width/shape
✧ Design of the full vapor source started

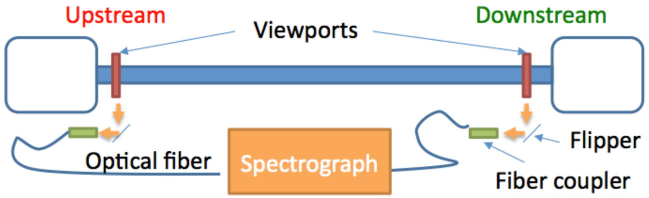
PLASMA LIGHT - WAKEFIELDS

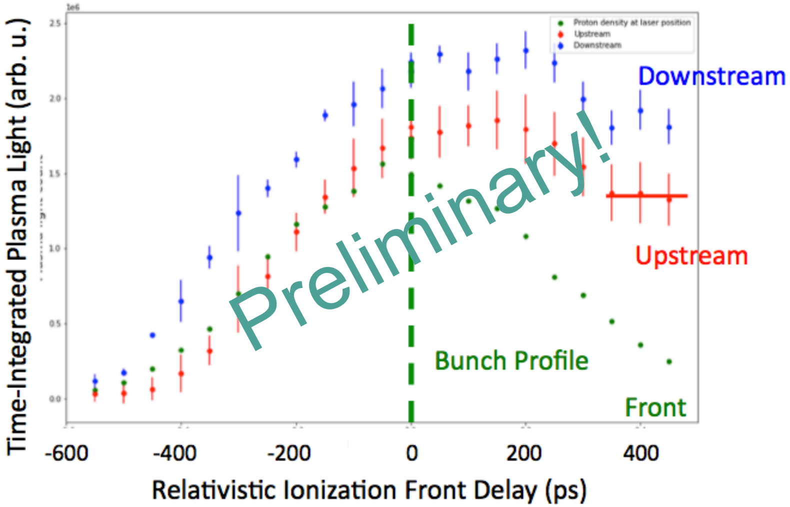
MAX-PLANCK-INSTITUT FÜR PHYSIK

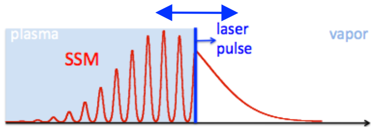
AWAKE

- ✧ Wakefields ultimately dissipate in the plasma
- ✧ Is Rb atomic light intensity proportional to the amplitude of the wakefields?
  - ✧ Wakefields sustained by plasma e- oscillations
  - ✧ Collisions with ions/neutral produce light

Preliminary!

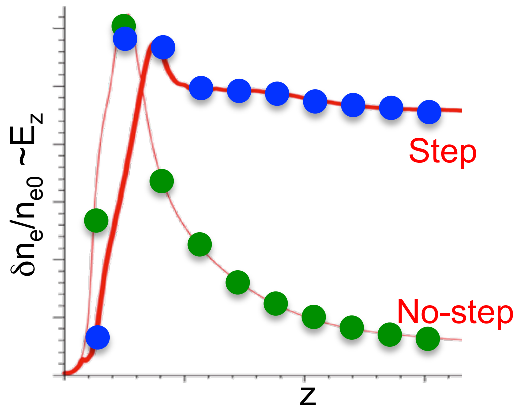


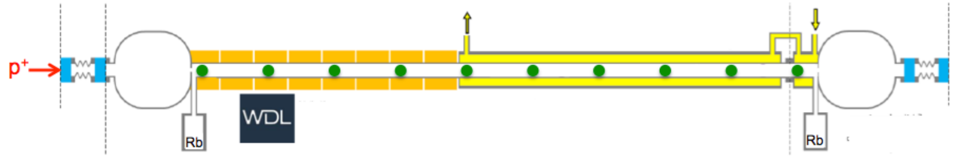




Run 2a:
RIF scan

Run 2b:
Wakefields
Diagnostic

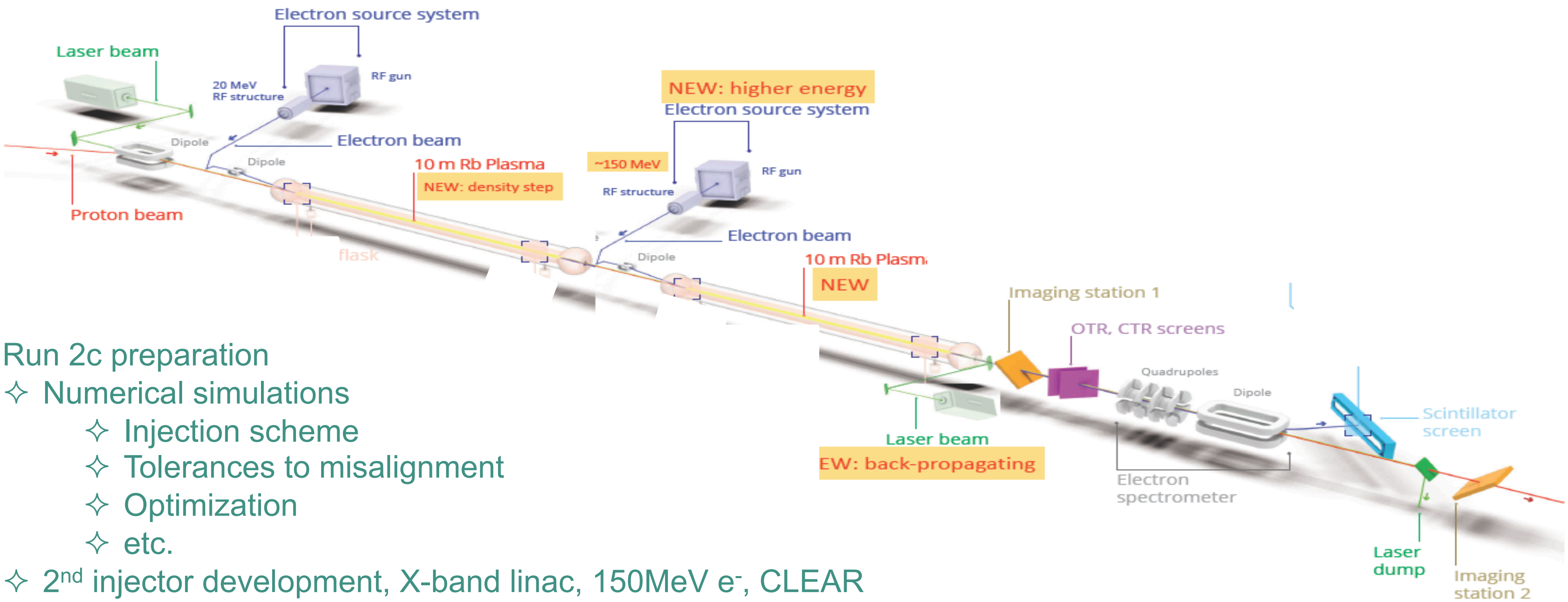




M. Bergamaschi, J. Pucek

- ✧ Plasma light / wakefields' amplitude correlation (seed wakefields, upstream)
- ✧ Further measurements needed

Run 2



Run 2c preparation

- ✧ Numerical simulations
  - ✧ Injection scheme
  - ✧ Tolerances to misalignment
  - ✧ Optimization
  - ✧ etc.
- ✧ 2nd injector development, X-band linac, 150MeV e-, CLEAR
- ✧ Vapor source and injection region
- ✧ Ionizing laser, optics, diagnostics, etc.

Run 2d preparation

- ✧ Plasma source development in CERN lab: helicon, discharge

Scalable Plasma Sources

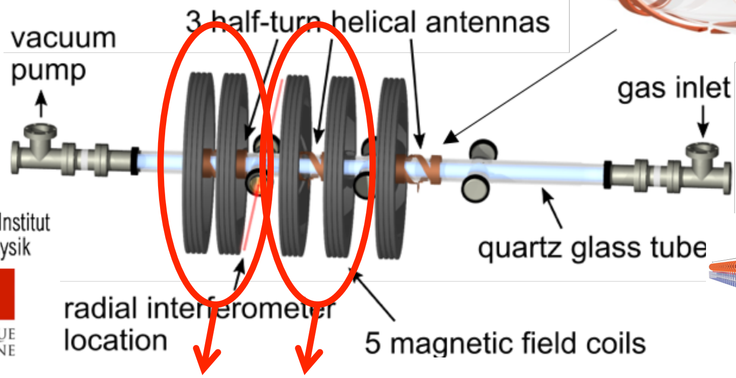
✧Laser ionization does not scale to long plasma lengths (100m-1km)

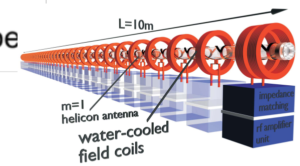
✧Plasma source development laboratory at CERN

✧Helicon source: magnetized RF discharge

1 m helicon plasma cell from IPP-Greifswald @ CERN

Buttenschön, PPFC 60(7), 075005 (2018)



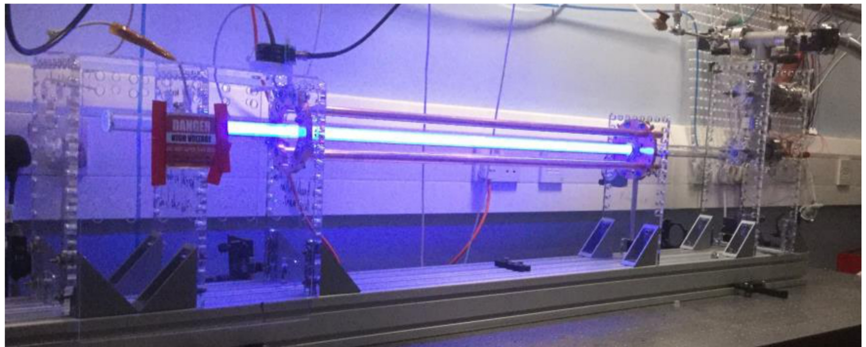


Max-Planck-Institut für Plasmaphysik

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

✧Unit cell (2 B-coils + RF antenna) that can be stacked…

✧Pulsed discharge



1.5 m discharge plasma source @ Imperial College

TÉCNICO LISBOA

Imperial College London

✧Replace Rb accelerator plasma source by scalable source!

Run 2

- Cost and Schedule review on Nov. 18, 2021

Run 2a:

- Request 15 weeks of p^+ beam (2-week periods), clear goals:
  - eSSM at high plasma density ($7x10^{14}cm^{-3}$)
  - eSSM – SMI competition or interference
  - Hosing studies
  - SSM characterization
  - Cherenkov e-BPMs
  - SM in Rubidium plasma ionized non-resonantly
  - Plasma light as diagnostic for wakefields

- Run 2b: new vapor/plasma source with density step installed during 2022-23 YETS

- Possible experiments with discharge source with (4+6)m plasmas

- Sustained simulation studies
  - Complement experimental results
  - Inform new experiments
  - Design future experiments

SUMMARY

- ✧Very successful Run 1
- ✧Clear plan/roadmap toward an accelerator for particle physics applications
- ✧Run 2 has started:
  - ✧First 5 weeks of Run 2a (2021-22) showed e-seeded self-modulation (e-SSM) at low plasma density
  - ✧Run 2b (2023-24), maintaining large accelerating gradient with plasma density step
  - ✧Run 2c (2027-..), external injection of e-bunch, acceleration to multi GeVs, bunch quality
  - ✧Run 2d, scalability of acceleration, development of scalable plasma source
- ✧Application to particle physics following Run 2

AWAKE Run 2 Timeline

Thank you to my collaborators!
… and to CERN …

Thank you!

http://www.mpp.mpg.de/~muggli
muggli@mpp.mpg.de