Outlook for AWAKE run #2

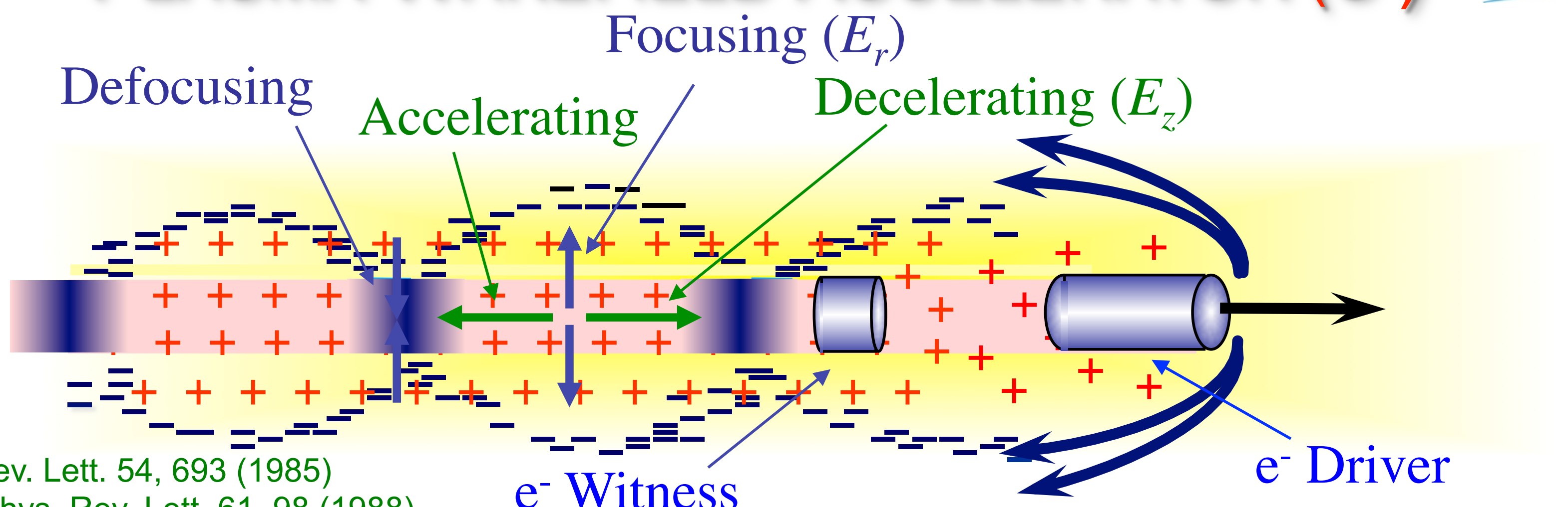
(discuss new or special diagnostics)

Patric Muggli
Max Planck Institute for Physics
Munich
muggli@mpp.mpg.de
https://www.mpp.mpg.de/~muggli

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

MAX-PLANCK-GESELLSCHAFT

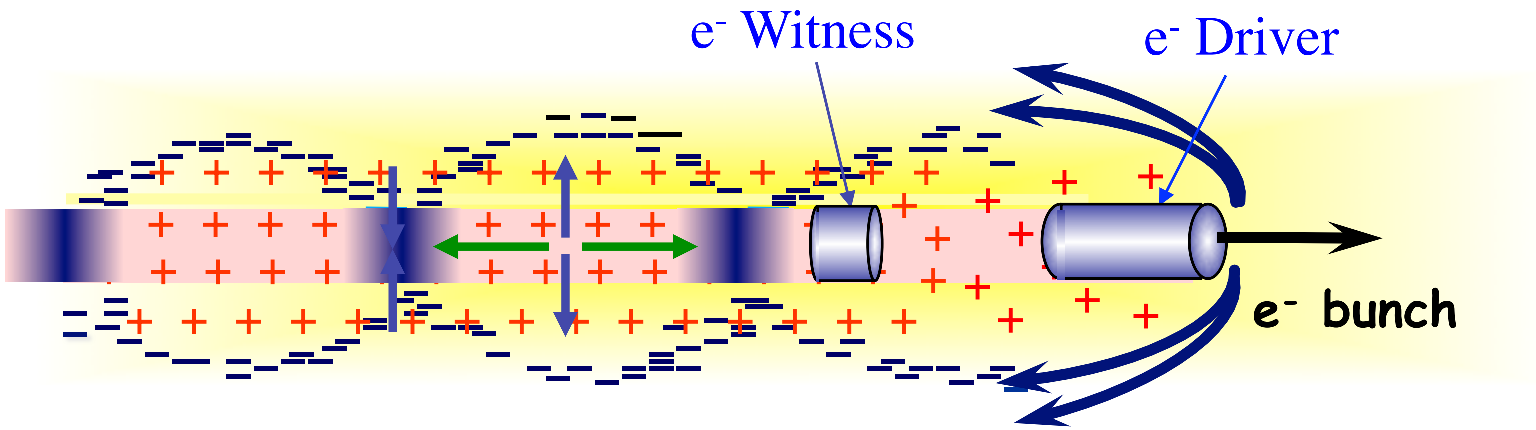
PLASMA WAKEFIELD ACCELERATOR (e^-)



Chen, Phys. Rev. Lett. 54, 693 (1985)
Rosenzweig, Phys. Rev. Lett. 61, 98 (1988)

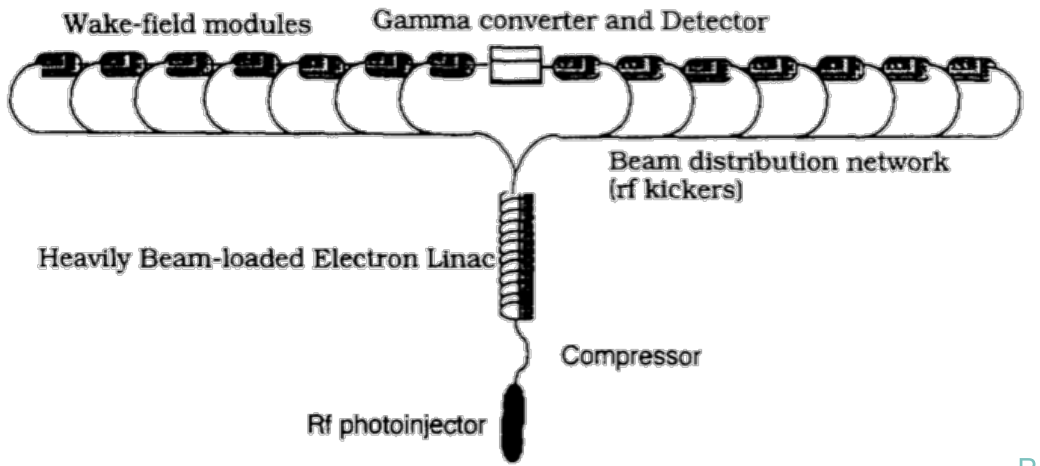
- Plasma wave/wake excited by a relativistic particle bunch
- Plasma e^- expelled by space charge force => deceleration + focusing (MT/m)
- Plasma e^- rush back on axis => acceleration, GV/m
- Ultra-relativistic driver => ultra-relativistic wake
  => no dephasing
- Plasma is already (at least) partially ionized => sustains large E-fields
- Can be driven by particle bunch (PWFA) or laser pulse (LWFA)

REACHiNG HiGH ENERGY?

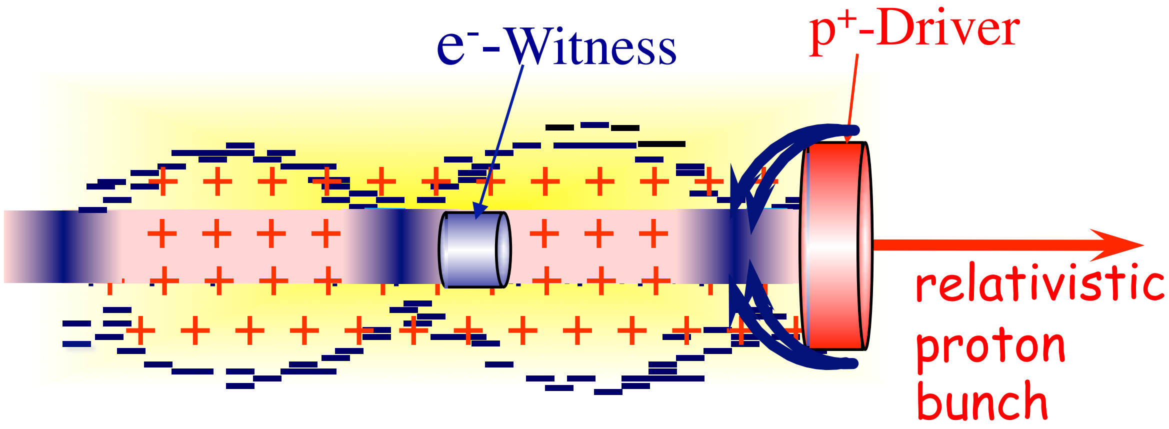


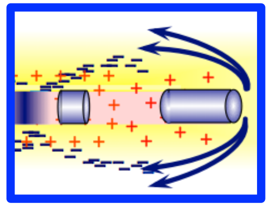
- ILC, 0.5TeV bunch with $2\times10^{10}e^-$ ~1.6kJ
- SLAC, 42GeV bunch with $2\times10^{10}e^-$ ~126J
- SLAC-like driver for staging (FACET= 1 stage, collider 10^+ stages)

J. Rosenzweig et al. / Nucl. Instr. and Meth. in Phys. Res. A 410 (1998) 532–543



p⁺-DRiVEN PWFA? YES. BUT WHY?





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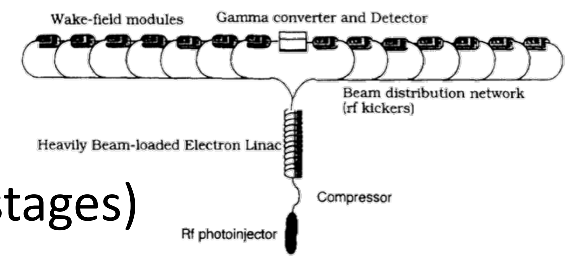
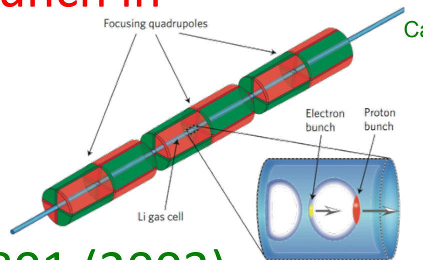
J. Rosenzweig et al./Nucl. Instr. and Meth. in Phys. Res. A 410 (1998) 532–543



✧SPS, 400GeV bunch with $10^{11}p^+$ ~6.4kJ
LHC, 7TeV bunch with $10^{11}p^+$ ~112kJ

✧A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage!

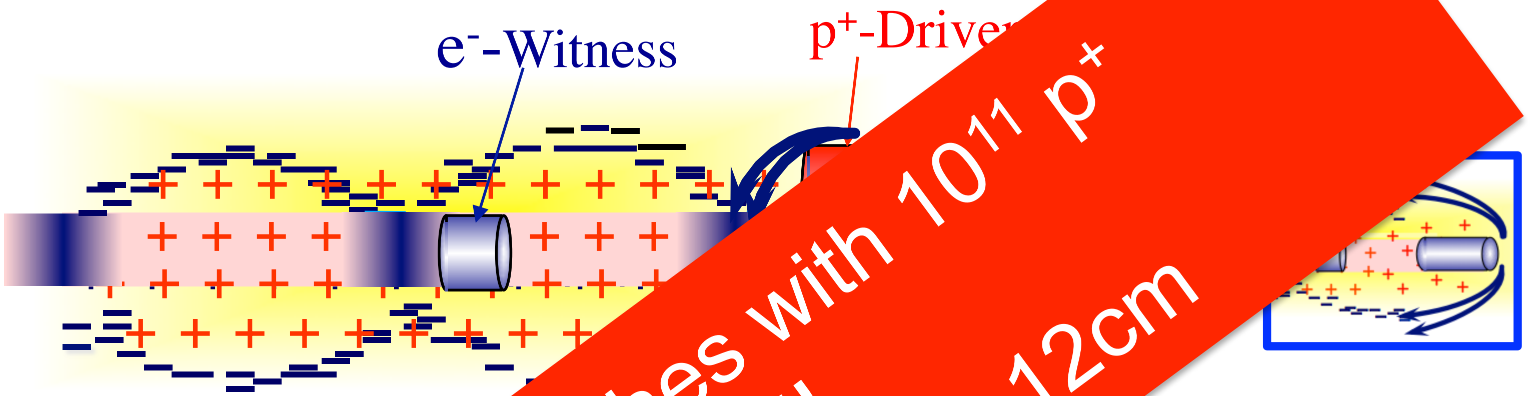


Caldwell, Nat. Phys. 5, 363, (2009)

✧Large average gradient! (≥1GeV/m, 100's m)

✧Wakefields driven by e^+ bunch: Blue, PRL 90, 214801 (2003)

p^+-DRIVEN PWFA? YES. BUT WHY?

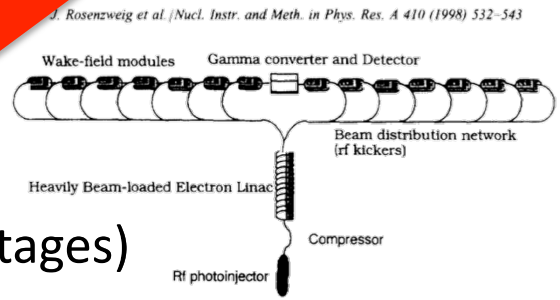


Short (100µm) bunches with 10^{11} p^+
do not exist!!!
CERN PS-SPS-LHC σ_z~6-12cm

✧ILC, 0.5TeV bunch with 2x10^{10}

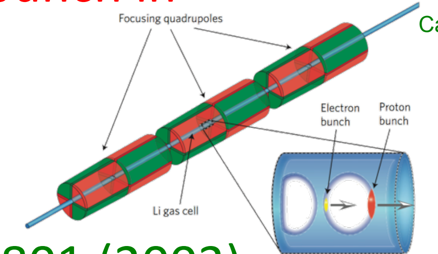
✧SLAC, 42GeV bunch with

✧SLAC-like driver f ... ollider 10$^+$ stages)



✧SPS, 400Ge ... ~6.4kJ
LHC, ... ~112kJ

✧ ... ould produce an ILC bunch in

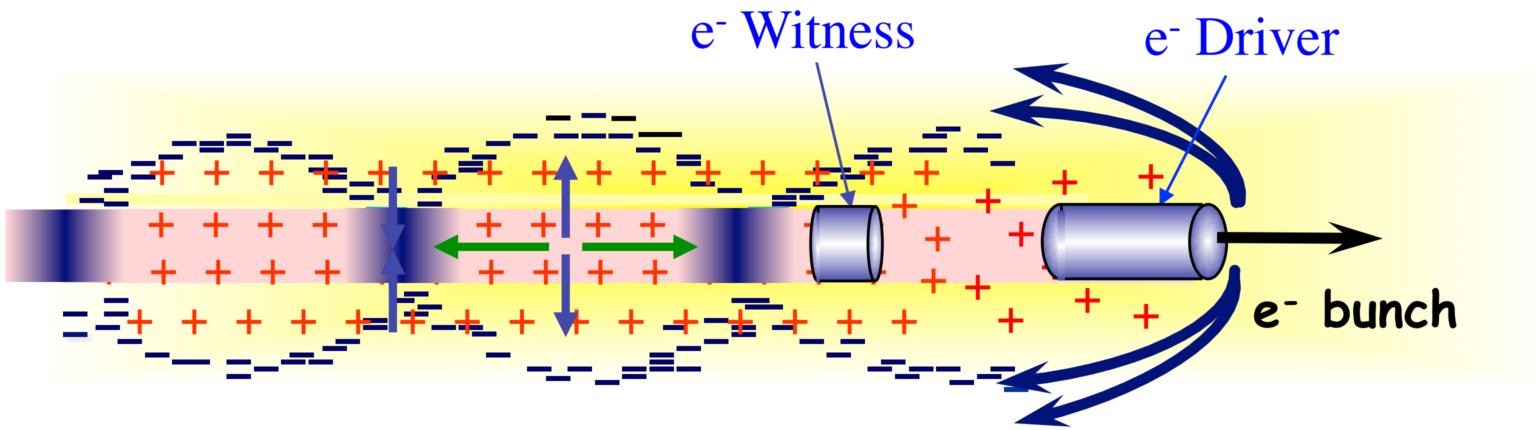


Caldwell, Nat. Phys. 5, 363, (2009)

✧Larg ... dient! (≥1GeV/m, 100's m)

✧Wakefie ... driven by e$^+$ bunch: Blue, PRL 90, 214801 (2003)

PWFA ENERGY FLOW



✧Drive (e^-, p^+) and witness (e^-, e^+) must fit within the structure

✧Linear theory ($n_b << n_e$) scaling:

$$E_{acc} \cong 110(MV/m)\frac{N/2\times10^{10}}{(\sigma_z/0.6mm)^2} \approx N/\sigma_z^2$$

$@\ k_{pe}\sigma_z \approx \sqrt{2}$ (with $k_{pe}\sigma_r << 1$)

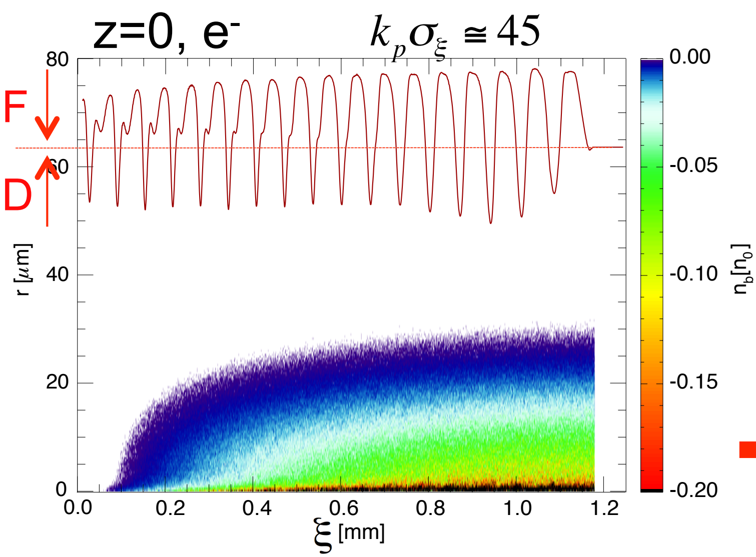
$$k_{pe} = \omega_{pe}/c \propto n_e^{1/2}$$

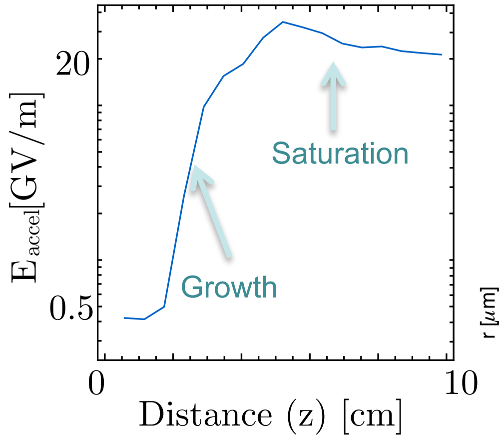
✧AWAKE: σ_z=6-12cm => E_{acc}~MV/m

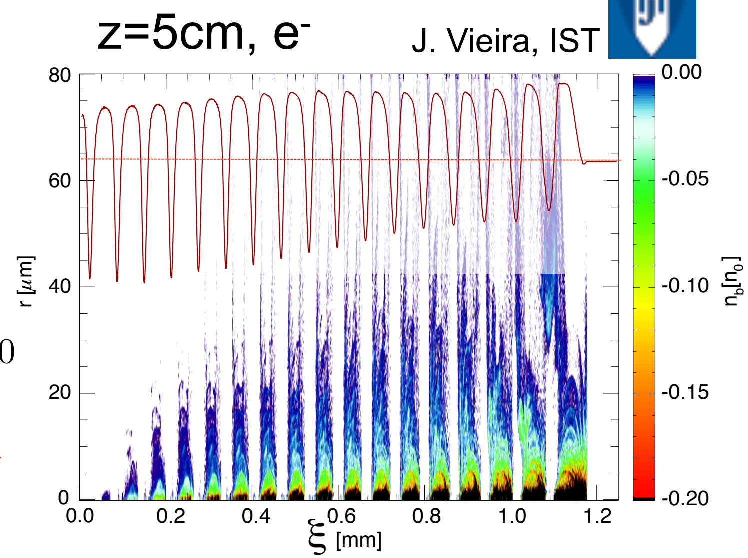
✧Instead: $k_{pe}\sigma_r$=1 => σ_r=200µm => n_e=7x10^{14}cm^{-3}, but $k_{pe}\sigma_z$>>1

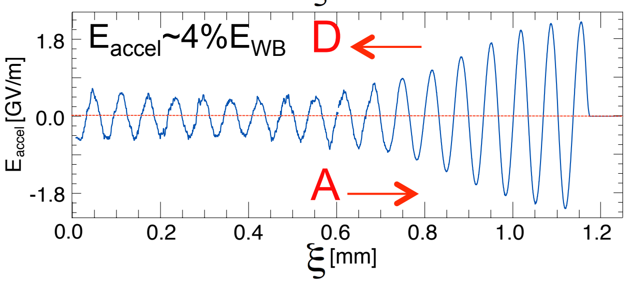
✧Need self-modulation to create $k_{pe}\sigma_z$~1 to reach ~1GV/m

SEEDED SELF-MODULATiON (SSM)

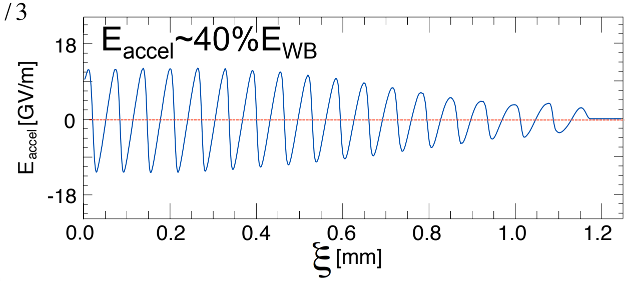








$$N_{exp} \cong \frac{3\sqrt{3}}{4}\left(\frac{n_b}{n_e}\frac{m_e}{\gamma M_b}\left(k_p|\xi|\right)\left(k_p z\right)^2\right)^{1/3}$$



Grows along the bunch & along the plasma

Pukhov et al., PRL 107, 145003 (2011)
Schroeder et al., PRL 107, 145002 (2011)

- ✧Initial small transverse wakefields modulate the bunch density with period $\sim\lambda_{pe} << \sigma_{z,\xi}$
- ✧Associated longitudinal wakefields reach large amplitude through resonant excitation

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

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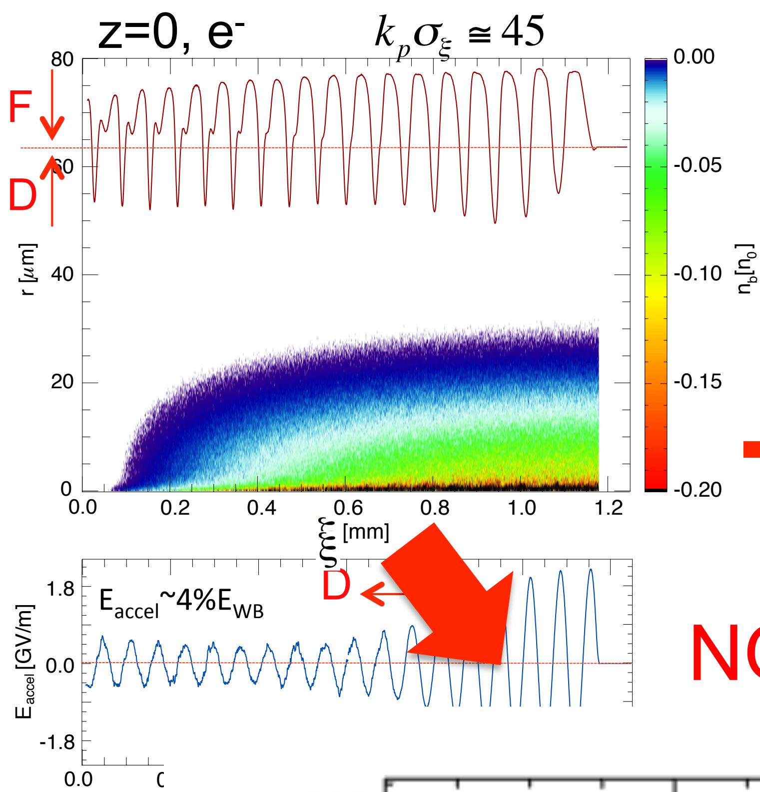
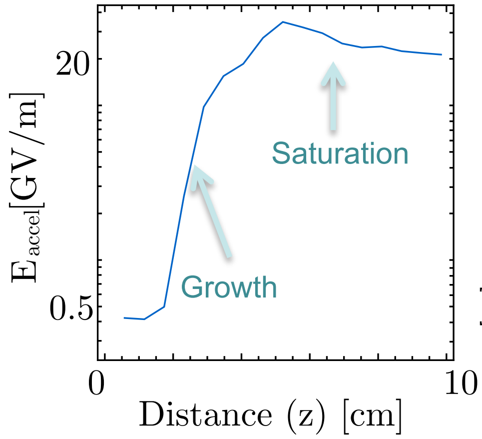
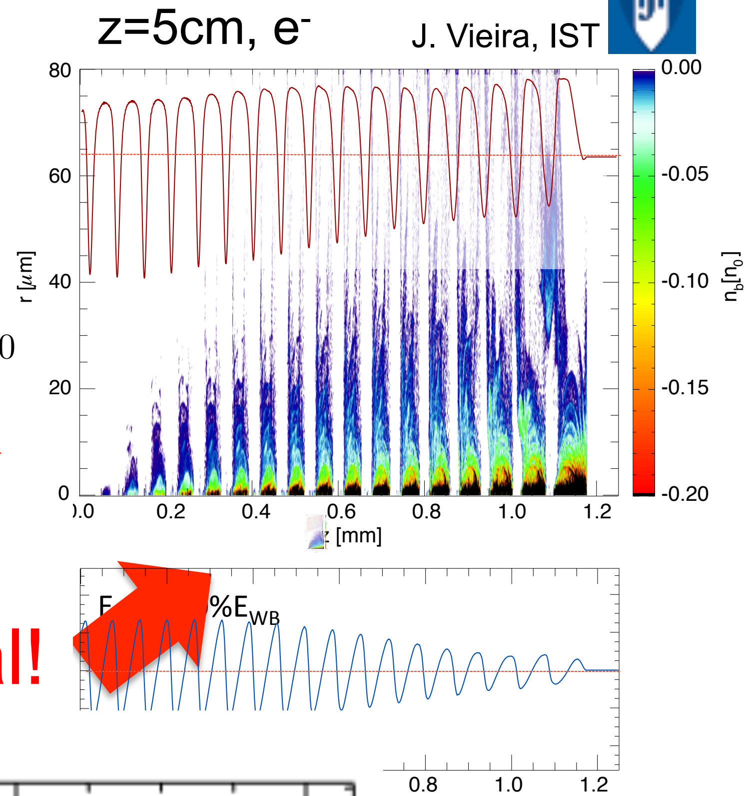
(Werner-Heisenberg-Institut)

SEEDED SELF-MODULATiON (SSM)

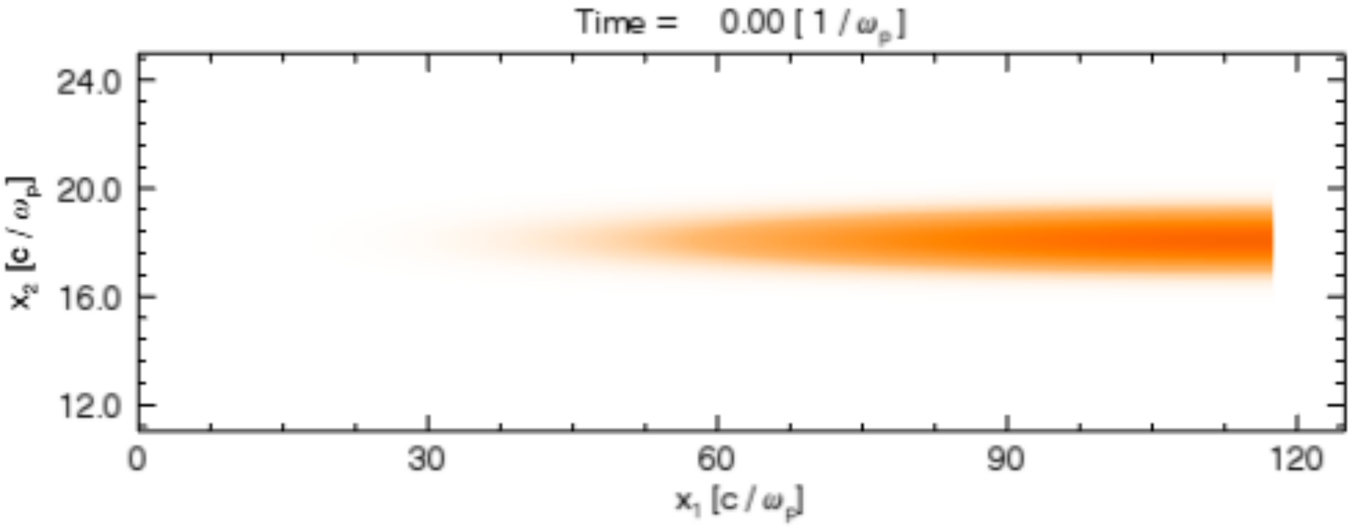
AWAKE







Radial!
NOT longitudinal!



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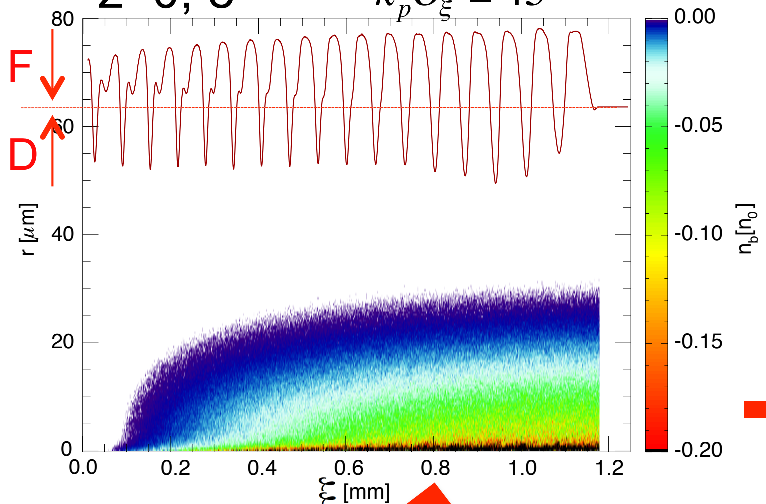
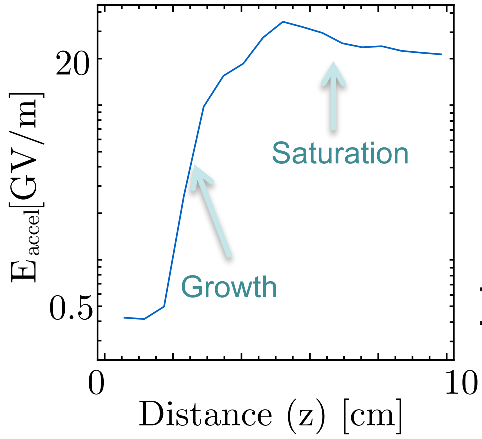
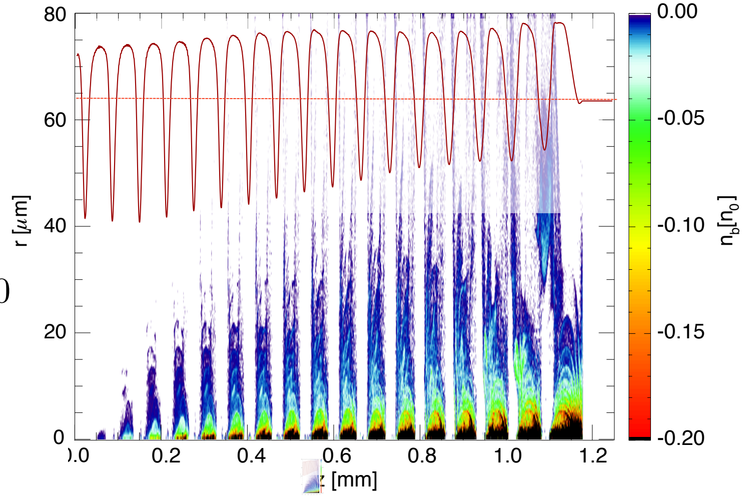
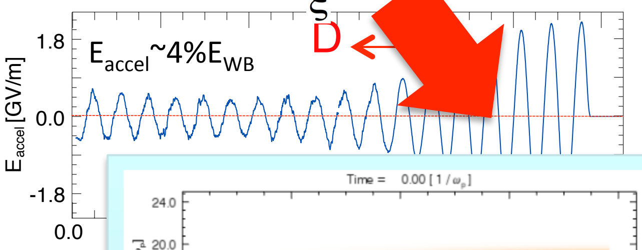
SEEDED SELF-MODULATiON (SSM)

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









Radial!

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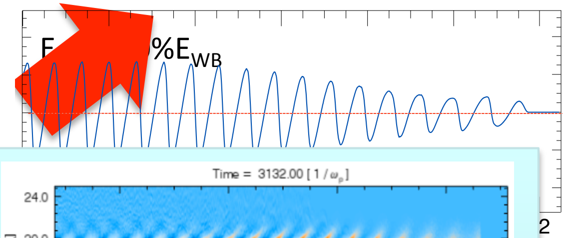
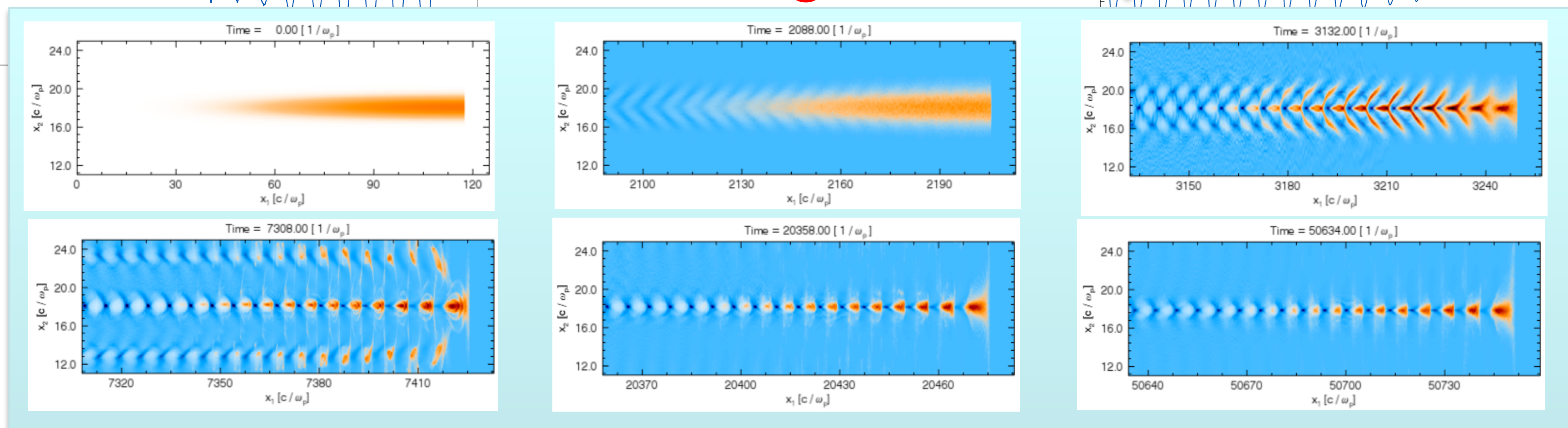




AWAKE RUN 1 GOALS

✧Get approved at CERN!

Date: September 23, 2013 10:29:55 AM GMT+02:00
To: Frederick Bordry <Frederick.Bordry@cern.ch>, Roberto Saban <Roberto.Saban@cern.ch>, Paul Collier <Paul.Collier@cern.ch>, Jose Miguel Jimenez <Jose.Miguel.Jimenez@cern.ch>
Cc: Steve Myers <Steve.Myers@cern.ch>, Edda Gschwendtner <Edda.Gschwendtner@cern.ch>
Subject: AWAKE Project Leader Mandate

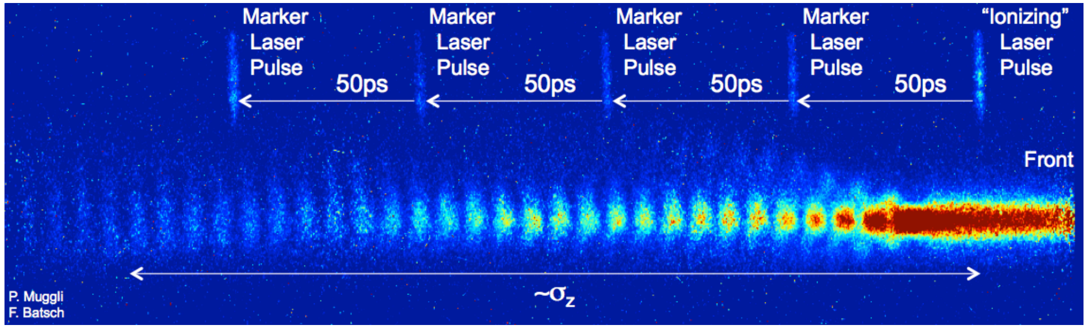
Dear All,

Please find attached the AWAKE Project Leader Mandate for distribution within your departments.

Kind regards,

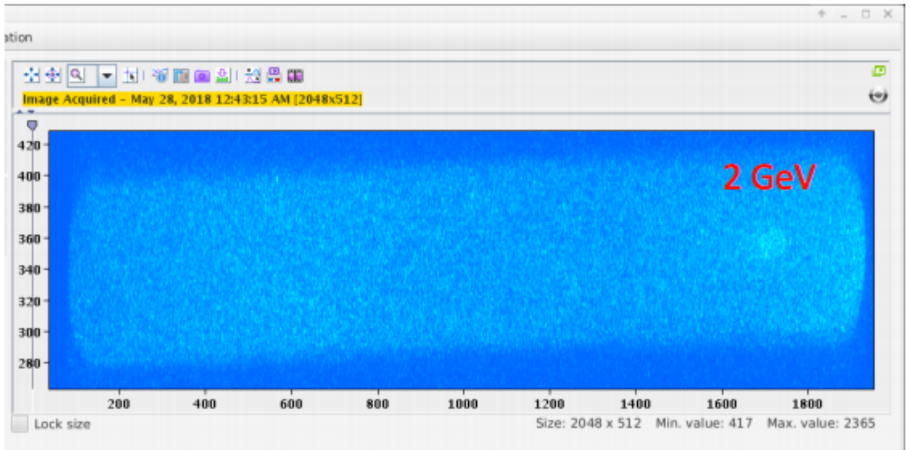
2013 ✓

✧Demonstrate self-modulation of the long p^+ bunch in a dense plasma



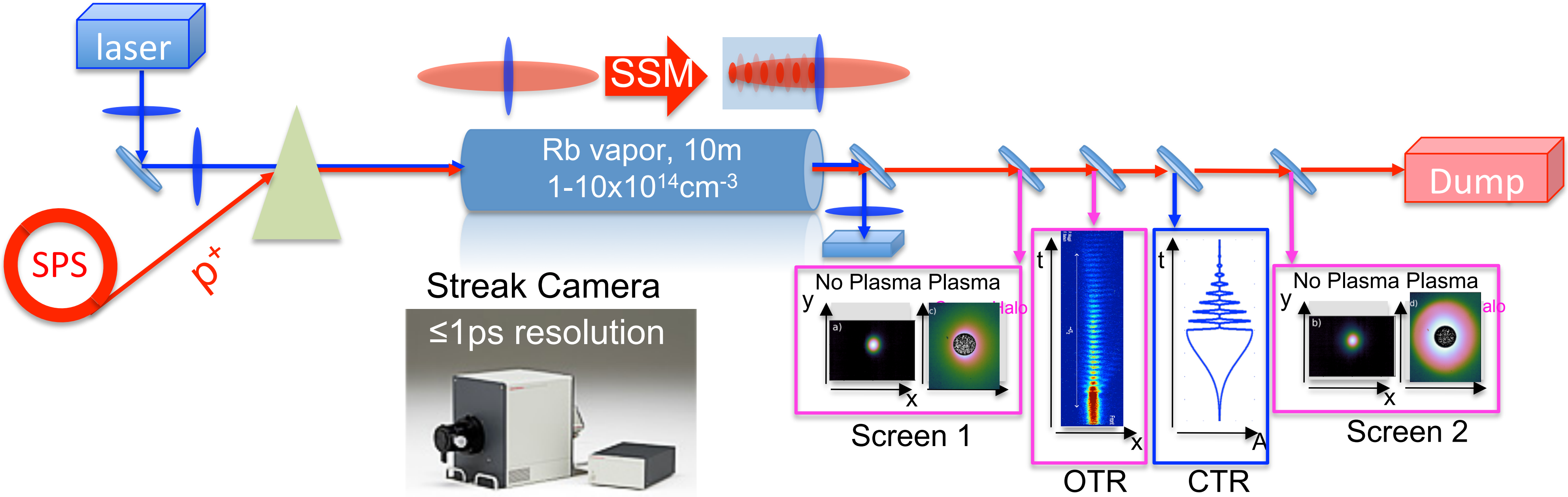
2017 ✓

✧Demonstrate acceleration of externally injected e^-



2018 ✓

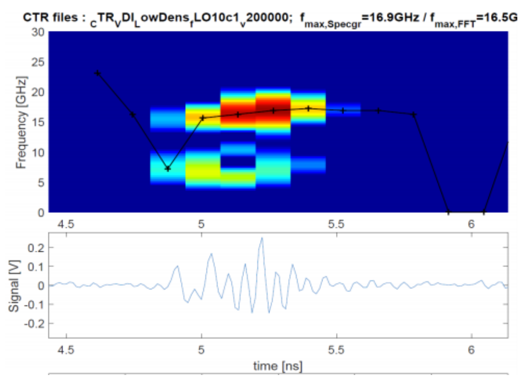
AWAKE RUN 1: SSM DIAGNOSTICS

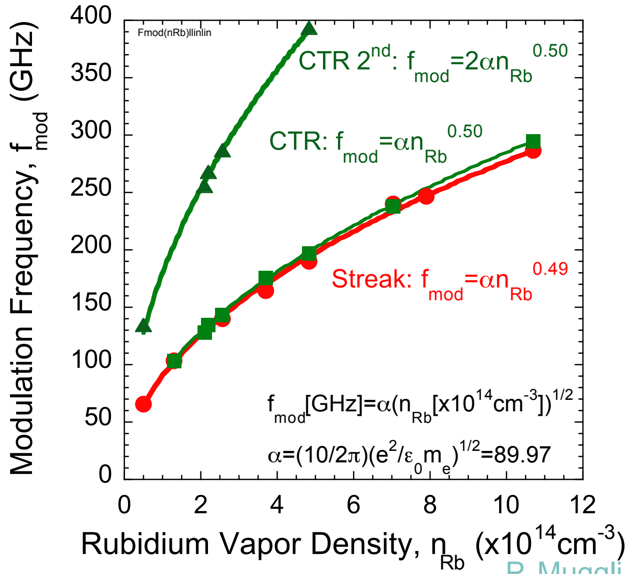


✧OTR+ streak camera for time-resolved p+ bunch images

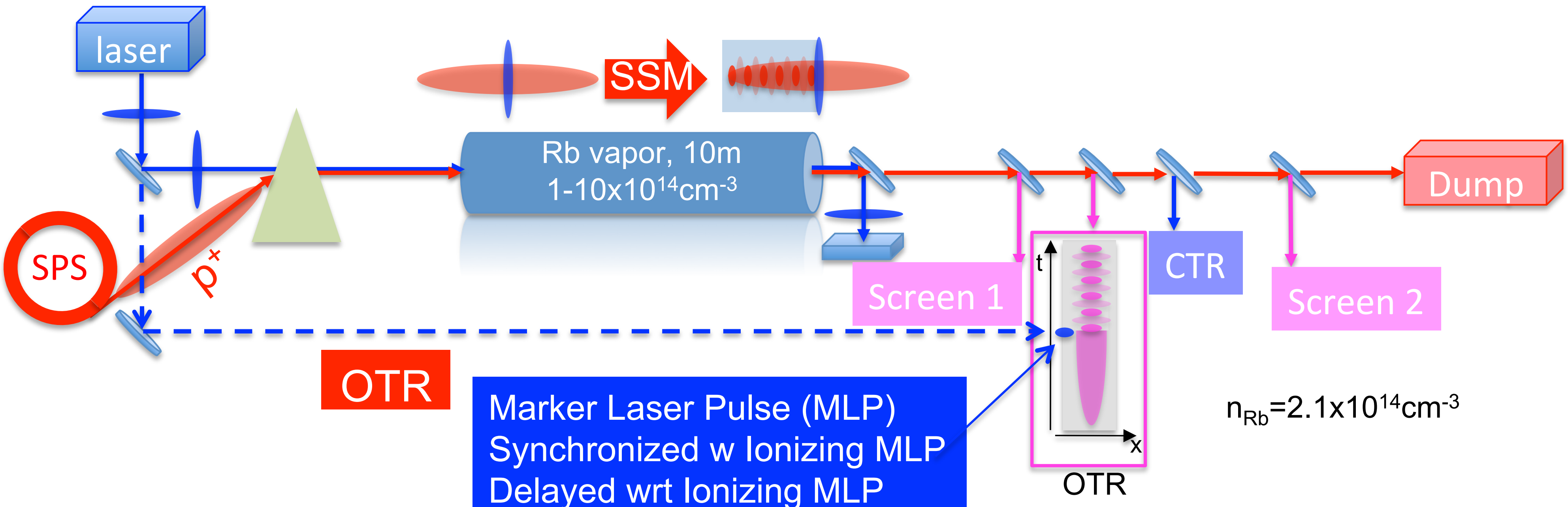
✧Screens in imaging stations

✧CTR frequency analysis diagnostic

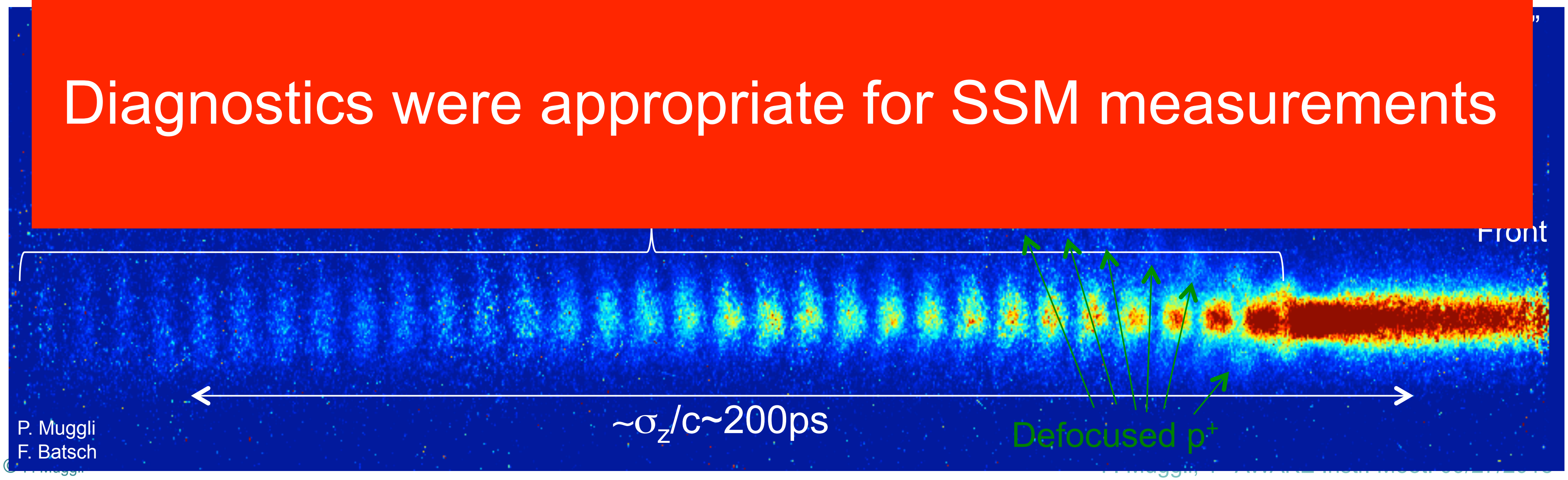




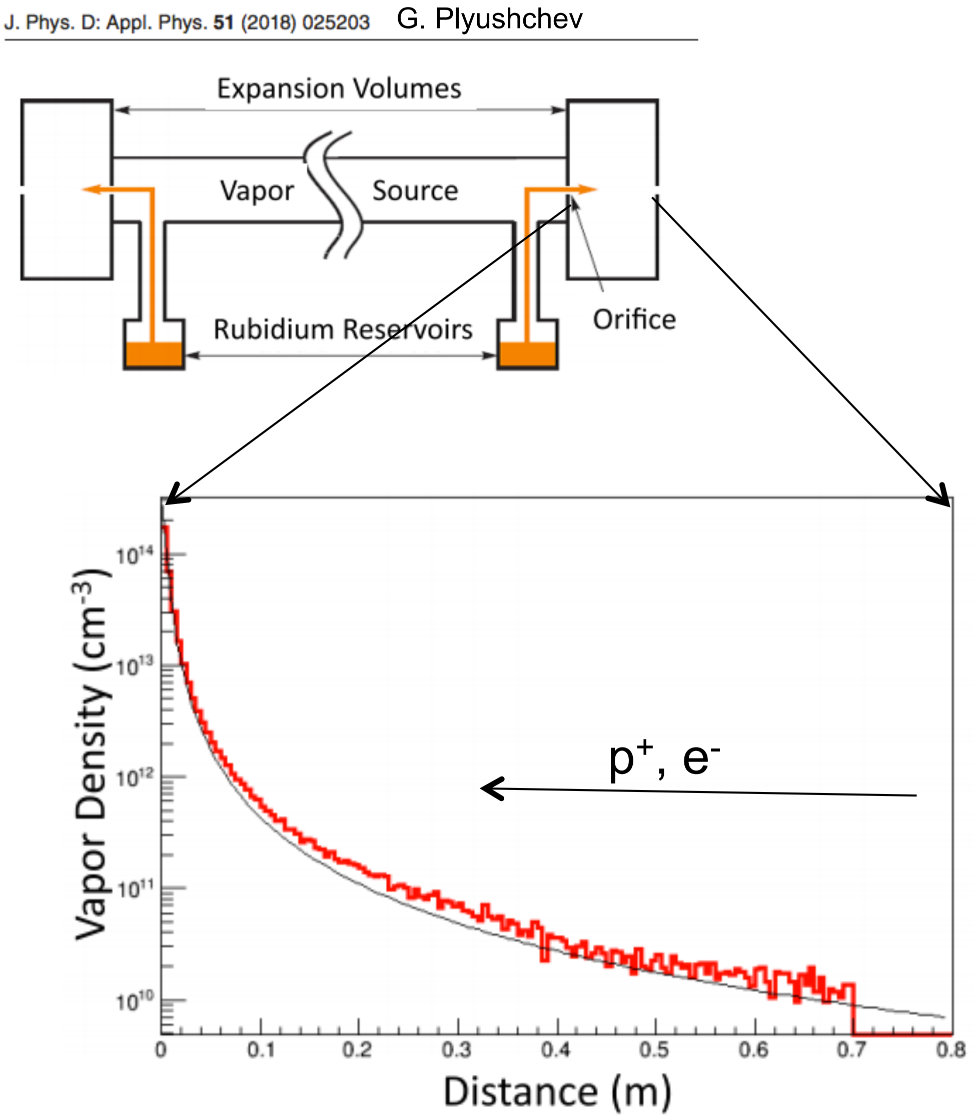
AWAKE RUN 1: SSM DiAGNOSTiCS



Diagnostics were appropriate for SSM measurements



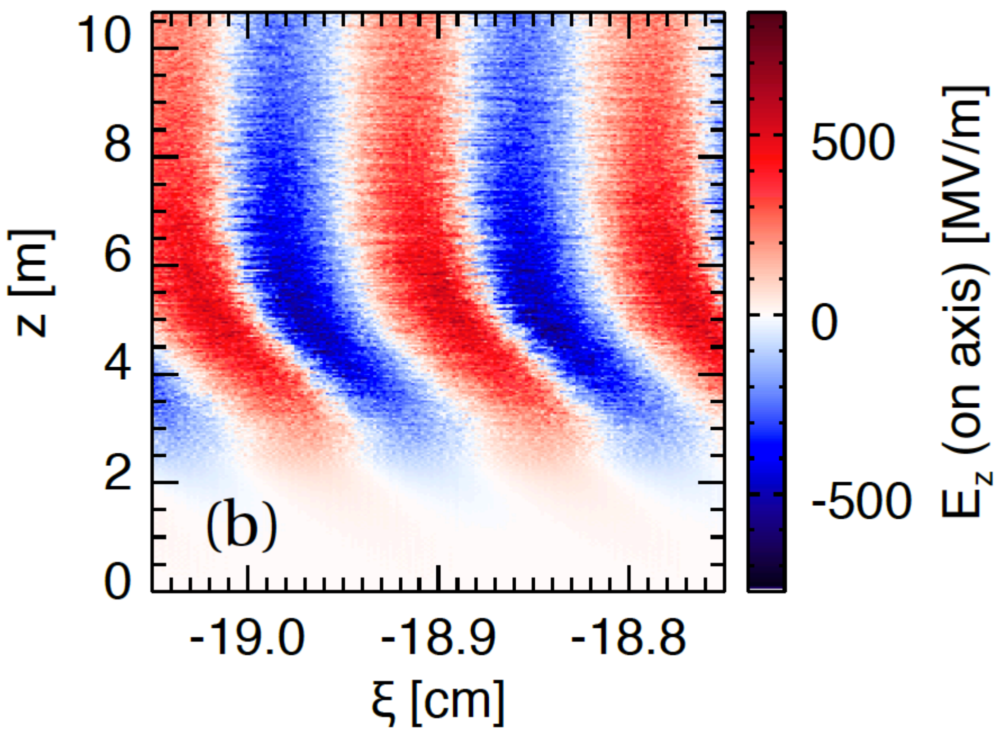
AWAKE: e⁻ INJECTiON



- ✧Vapor source has "density ramp" at ends
- ✧n_{Rb} ramp => n_e ramp
- ✧Wakefields focusing for drive bunch charge sign, i.e., defocusing for e^-

AWAKE: e⁻ INJECTiON

M. Moreira



- ✧Wakefields slower than drive bunch when SSM grows ...
- ✧Must inject at z>0
- ✧Run 1: side injection
- ✧Run 2: inject z>5m(?)

AWAKE: e⁻ INJECTiON

K. V. Lotov, Journal of Plasma Physics 78(04), 455 (2012).

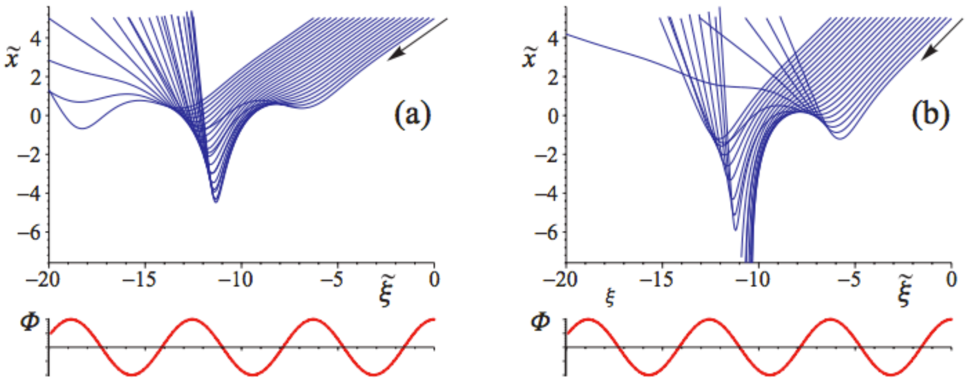
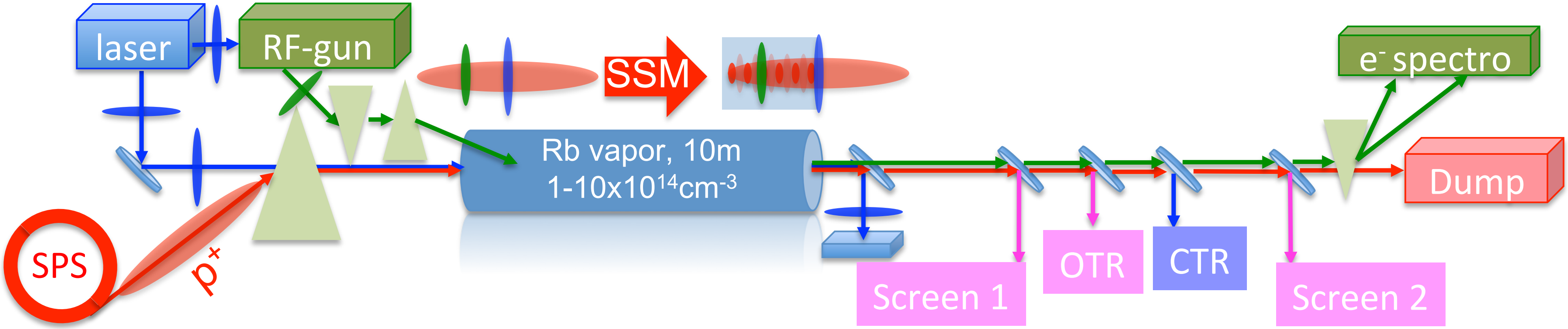


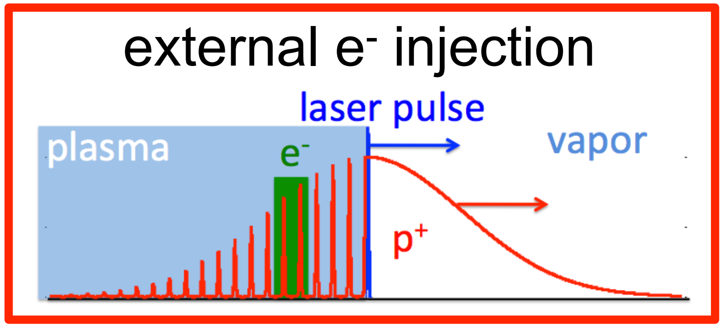
Figure 3. (Colour online) Family of electron trajectories for (a) $\tilde{v} = -0.7$, and (b) $\tilde{v} = -1$. Lower graphs show the location of potential wells and humps.

- ✧ e^- have to "cross" wakefields
- ✧ Complicated trajectories
- ✧ Low capture
- ✧ Dependencies on angle and position

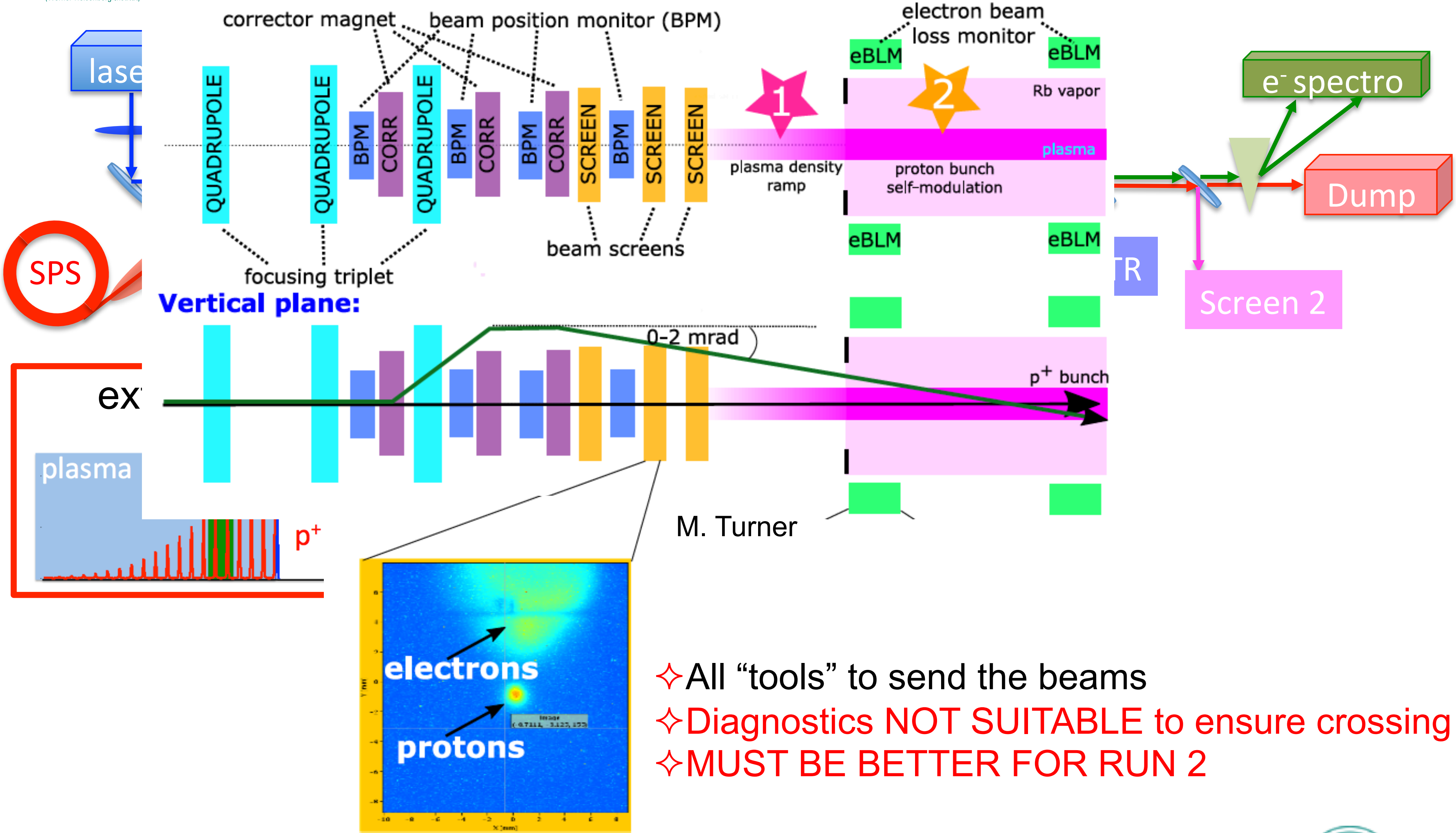
- ✧ Run 1 choice: $\sigma_{z,\, e-} > \lambda_{pe}$ => no <1ps timing required
- ✧ Run 2 must have $\sigma_{z,\, e-} << \lambda_{pe}$ => ~100fs timing required
- ✧ Timing between seed laser pulse and RF-gun laser pulse or e^- bunch

AWAKE Run 1: Accleration





AWAKE RUN 1: ACCELERATiON DiAGNOSTiCS



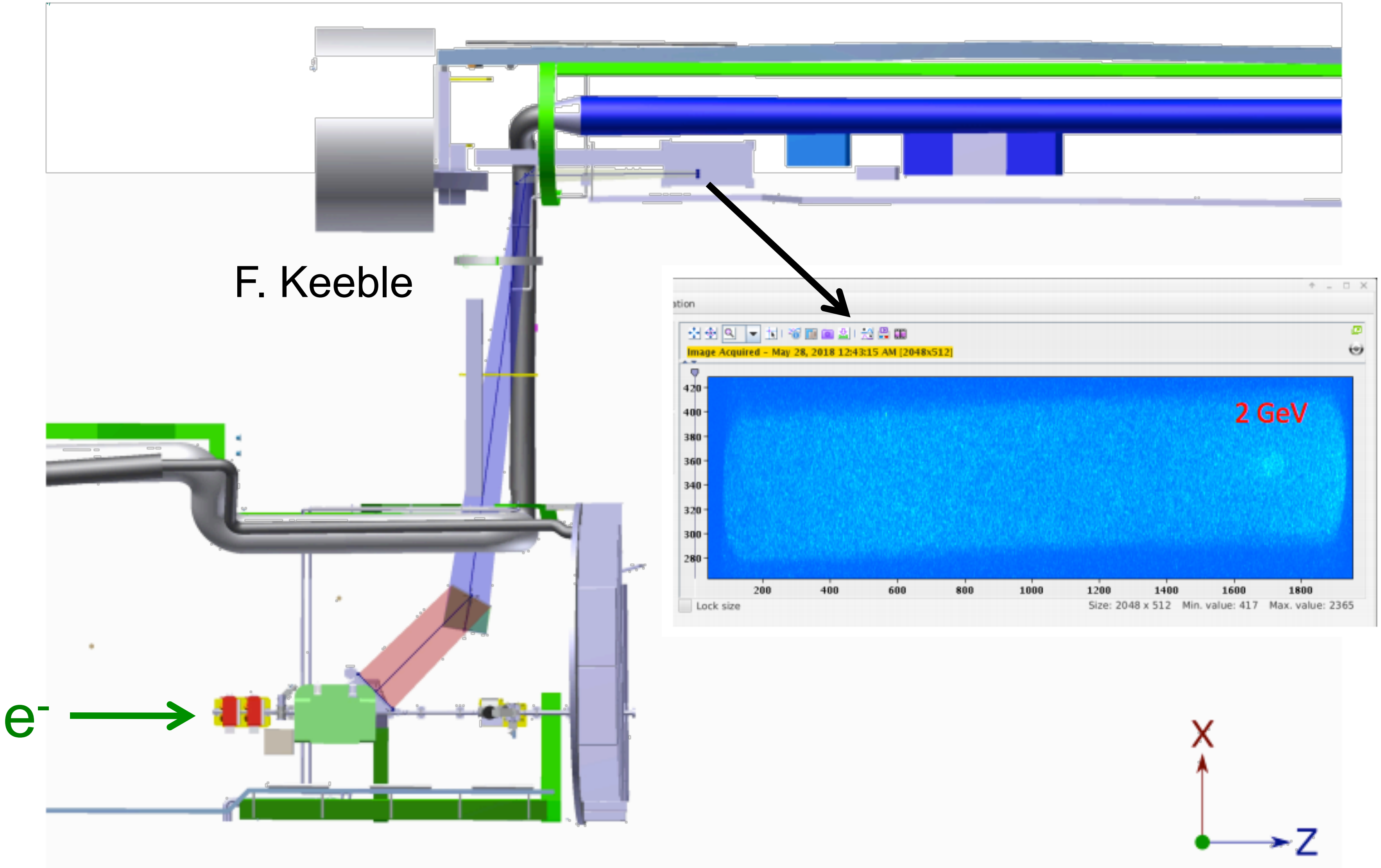
✧All "tools" to send the beams

✧Diagnostics NOT SUITABLE to ensure crossing

✧MUST BE BETTER FOR RUN 2

✧Debriefing from Run 1 to improve for Run 2!

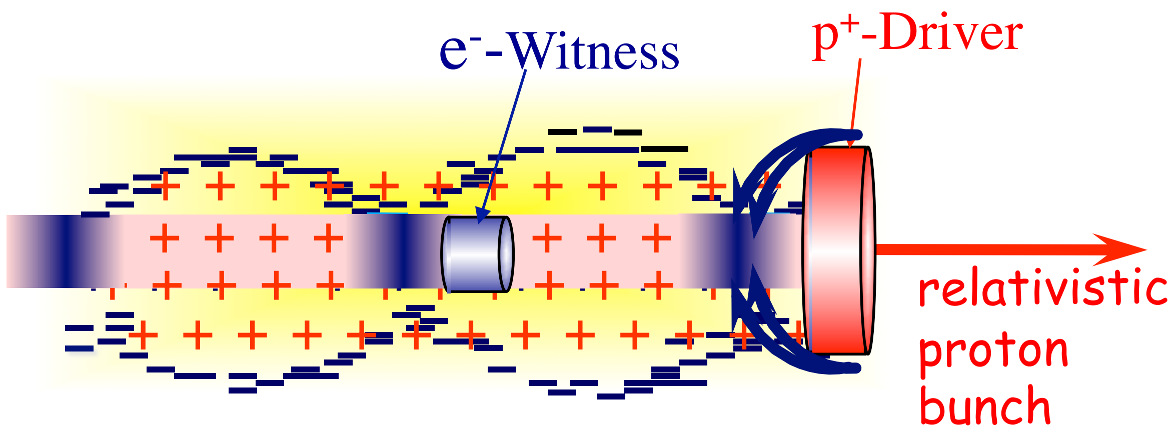
AWAKE RUN 1: ACCELERATION DIAGNOSTICS

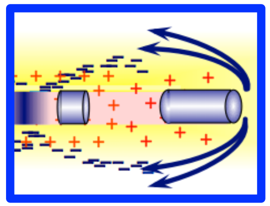


- ✧e⁻ spectrometer standard
- ✧Challenge: background from p^+ secondaries

AWAKE RUN 2: GOAL

✧Acceleration of an externally injected e^- bunch with small final ε and $\Delta E/E$ @ GeV





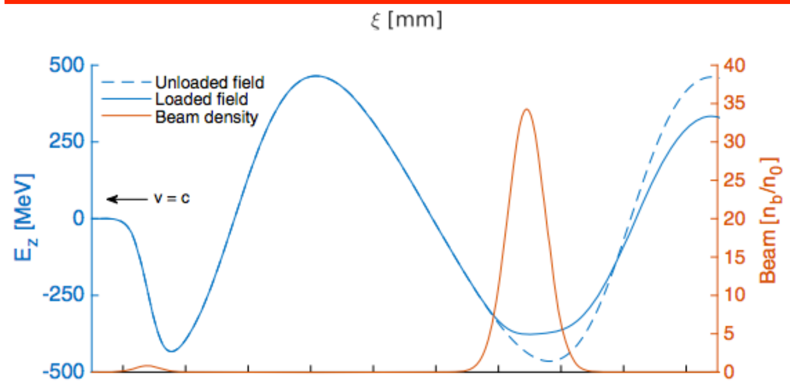
✧Challenge: put the witness e^- bunch in the right place
✧Preserve its quality (low emittance, narrow energy spread)
✧Scalability

AWAKE RUN 2: GOAL

✧Acceleration of an externally injected e^- bunch with small final ε and $\Delta E/E$ @ GeV

OLSEN, ADLI, and MUGGLI PHYS. REV. ACCEL. BEAMS **21,** 011301 (2018)

"From acceleration to accelerator!"
Goal of all advanced accelerator concepts

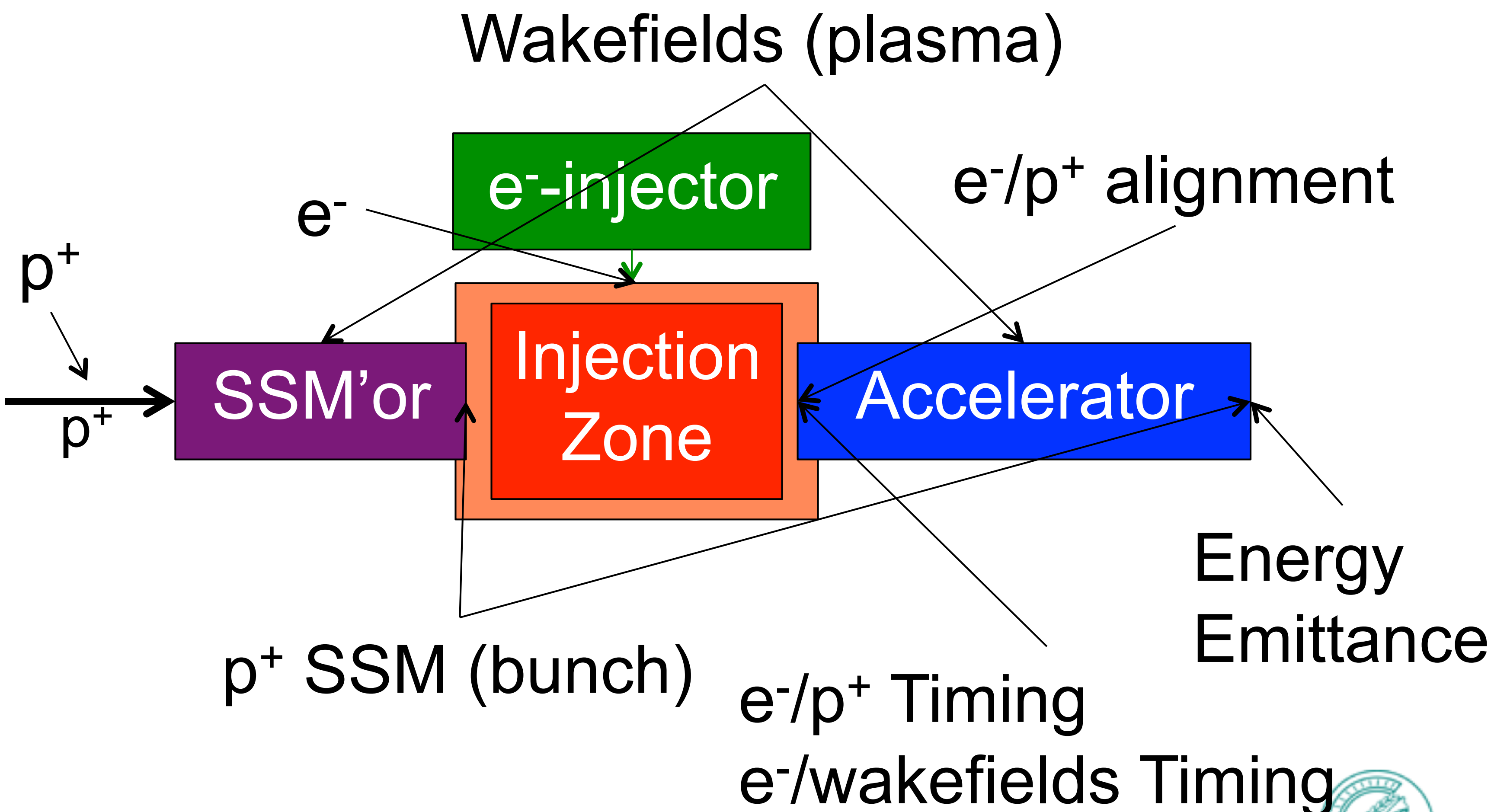


<u>Typical parameters</u>:
σ_z=60μm
σ_r=5.25μm
(matched for ε_N=2mm-mrad, n_e=7x10^{14}cm^{-3}, ~$\varepsilon_N^{1/4}$)
Q=100pC
Blow-out and beam loading
~73% charge with $\Delta\varepsilon_N/\varepsilon_N$<5%, $\Delta E/E$~%

✧Challenging parameters to produce with low energy particles (σ_r,σ_z)
✧Challenging to measure (σ_r)

AWAKE RUN 2: GOAL

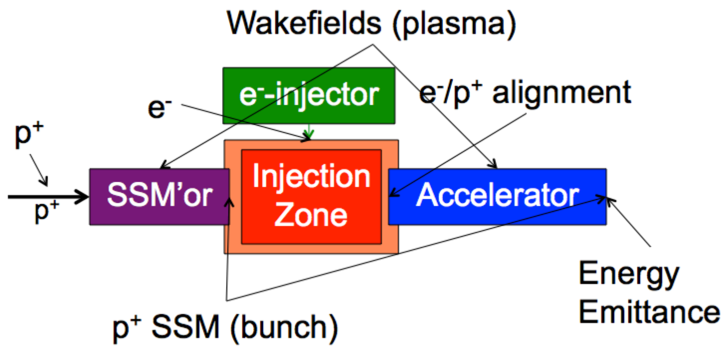
✧Acceleration of an externally injected e^- bunch with small final ε and $\Delta E/E$ @ GeV
✧Decouple SSM and acceleration



✧Plasma source(s) based on rubidium vapor and laser ionization!!!!
✧p^+ bunch at (1/20)Hz at best …

AWAKE RUN 2 DIAGNOSTICS

- p^+: standard beam line diagnostics
- p^+ SSM: OTR and streak camera, needed on every event!
- Wakefields (plasma): Schlieren, interferometry, photon acceleration, ???
- e^-: standard beam line diagnostics, screen-based?
- e^-/p^+ alignment: OTRs, screens, ???
- Timing
  - Timing e^-/p^+: online EOS (p^+ halo?)
  - Timing e^-/wakefields?
- Energy: spectrometer
- Emittance: single shot (β-tron, optical pepper pot, ???), separate e^-/p^+



- Laser-ionized, rubidium plasma imposes strong constraints (200°C, chemically reactive, metal deposition?, etc.
- p^+ bunch at (1/20)Hz at best …

SUMMARY

✧AWAKE Run 1 was very successful: SSM & acceleration of e⁻ to 2GeV

✧SSM and acceleration diagnostics were appropriate

✧Fell short on e⁻ injection diagnostics

✧AWAKE Run 2 is about e⁻ beam quality and needs (diagnostics):

✧Need in-situ spatial alignment screens (few μm level)

Excellent and new diagnostics are **absolutely** key for Run 2!

✧Alignment diagnostics are challenging (temperature and rubidium)

✧Energy measurement is OK

✧Some Run I diagnostics directly transfer, but debriefing would be beneficial

✧SSM diagnostics are key to the experiment

✧Many issues "solved on the fly"

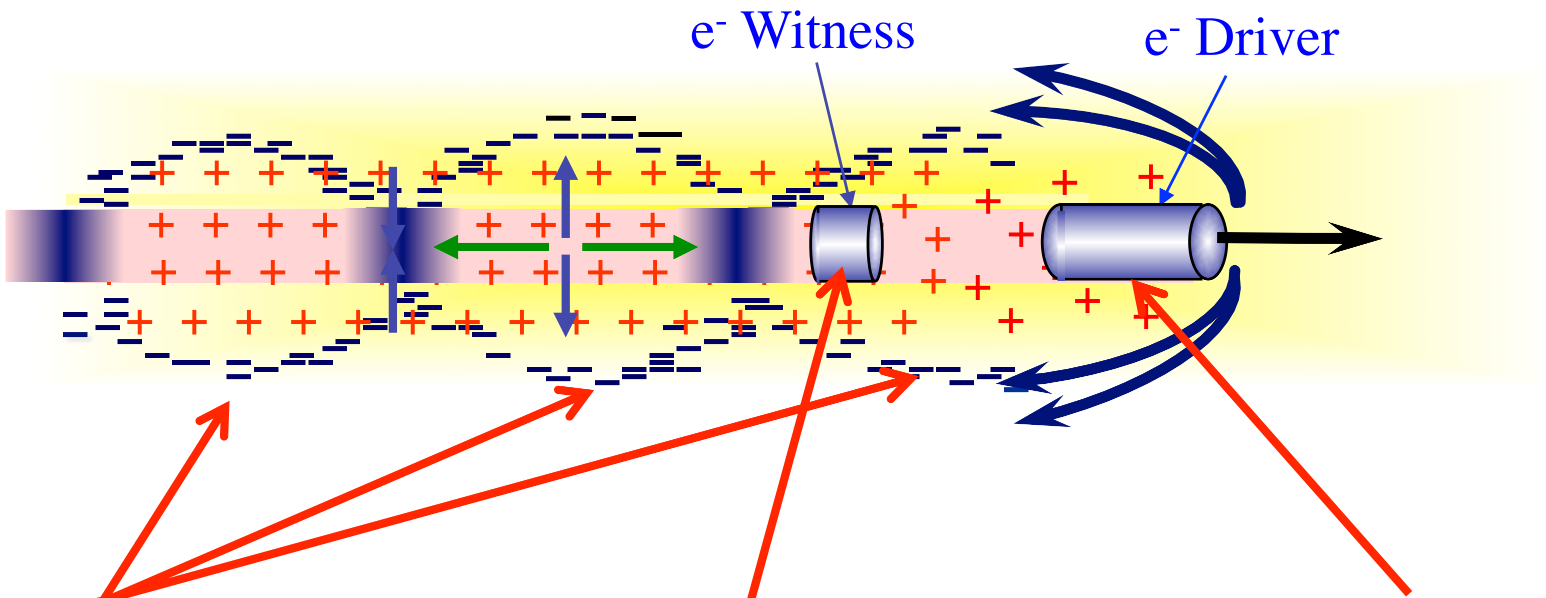
✧Bottom line: better diagnostics = better experiment

Thank you to my collaborators!

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

muggli@mpp.mpg.de

PWFA ENERGY FLOW

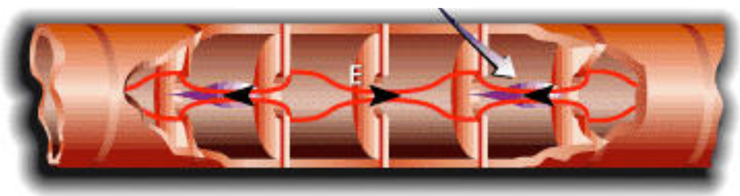


2) Energy is "stored" in the wakefields sustained by the oscillatory motion of the plasma e⁻, charge separation

3) Witness bunch can extract energy from the wakefields

1) Drive bunch loses energy driving the wakefields

Replaces:

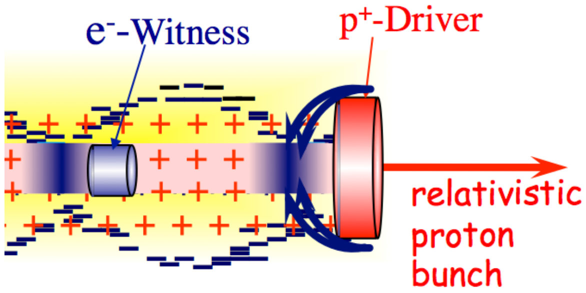


Replaces:

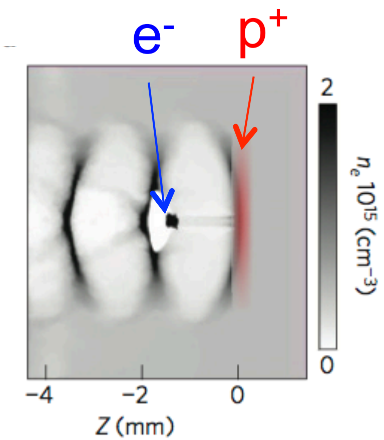
✧Is it a high gradient accelerator?

PROTON-DRIVEN PWFA

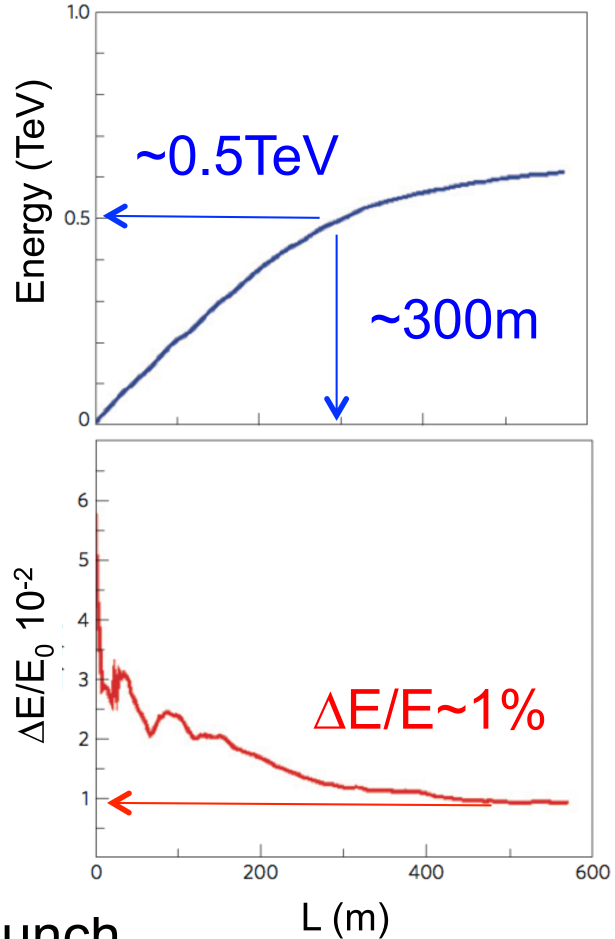
Caldwell, Nat. Phys. 5, 363, (2009)



	e^-:	p^+:
	E_0=10GeV	E_0=1TeV
		σ_z=100µm
	N=10^{10}	N=10^{11}
Single Stage	W_0=16J	W_0=16kJ
	W_f=1kJ	



Parameter	Symbol	Value	Units
Protons in drive bunch	N_P	10^{11}	
Proton energy	E_P	1	TeV
Initial proton momentum spread	σ_P/p	0.1	
Initial proton bunch longitudinal size	σ_z	100	µm
Initial proton bunch angular spread	σ_θ	0.03	mrad
Initial proton bunch transverse size	$\sigma_{x,y}$	0.43	mm
Electrons injected in witness bunch	N_e	1.5×10^{10}	
Energy of electrons in witness bunch	E_e	10	GeV
Free electron density	n_p	6×10^{14}	cm^{-3}
Plasma wavelength	λ_p	1.35	mm
Magnetic field gradient		1,000	$T m^{-1}$
Magnet length		0.7	m



- ✧Accelerate an e^- bunch on the wakefields of a p^+ bunch
- ✧Single stage, no gradient dilution
- ✧Gradient ~1 GV/m over 100's m
- ✧Operate at lower n_e ($6x10^{14}cm^{-3}$), larger $(\lambda_{pe})^3$, easier life …

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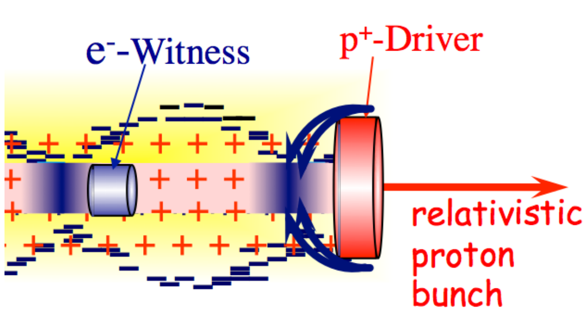

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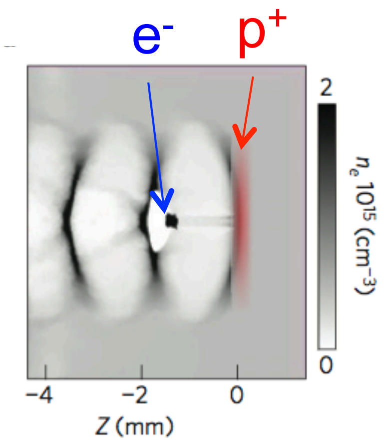
Single Stage



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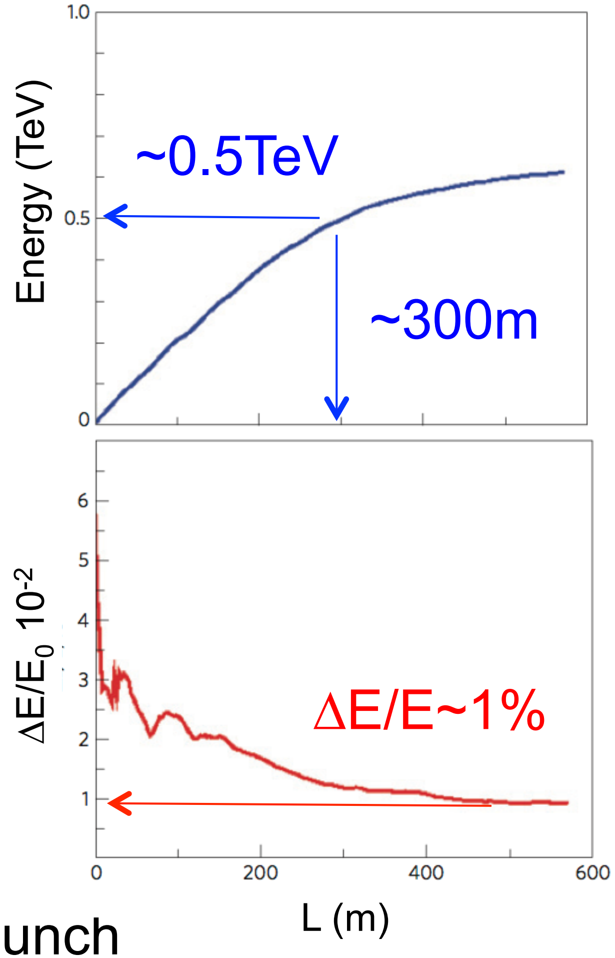

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