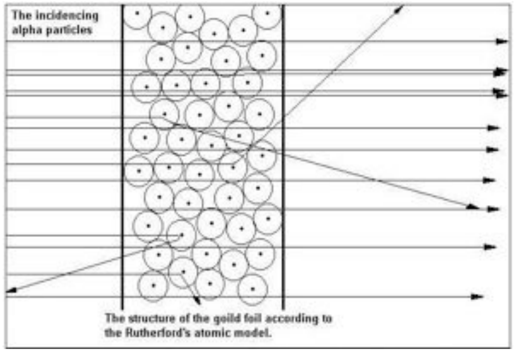
AWAKE, the Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN

Edda Gschwendtner, CERN
for the AWAKE Collaboration

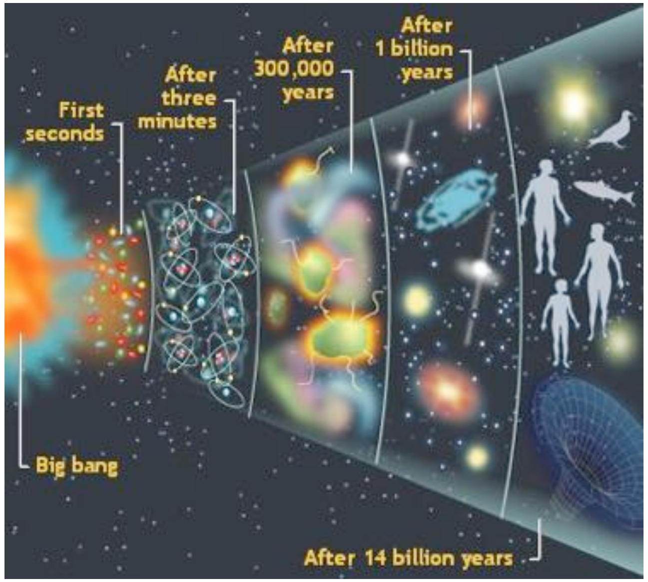
Outline

- Motivation
- Plasma Wakefield Acceleration
- AWAKE
- Outlook

Motivation: Increase Particle Energies



- Increasing particle energies **probe smaller and smaller scales of matter**
  - **1910:** Rutherford: scattering of MeV scale alpha particles revealed structure of atom
  - **1950ies:** scattering of GeV scale electron revealed finite size of proton and neutron
  - **Early 1970ies:** scattering of tens of GeV electrons revealed internal structure of proton/neutron, ie quarks.



- Increasing energies **makes particles of larger and larger mass accessible**
  - GeV type masses in 1950ies, 60ies (Antiproton, Omega, hadron resonances…
  - Up to 10 GeV in 1970ies (J/Psi, Ypsilon…)
  - Up to ~100 GeV since 1980ies (W, Z, top, Higgs…)
- Increasing particle energies **probe earlier times in the evolution of the universe.**
  - Temperatures at early universe were at levels of energies that are achieved by particle accelerators today
  - Understand the origin of the universe
- Discoveries went hand in hand with theoretical understanding of underlying laws of nature

  → **Standard Model** of particle physics

Motivation: High Energy Accelerators

- Large list of unsolved problems:
  - What is dark matter made of? What is the reason for the baryon-asymmetry in the universe? What is the nature of the cosmological constant? …

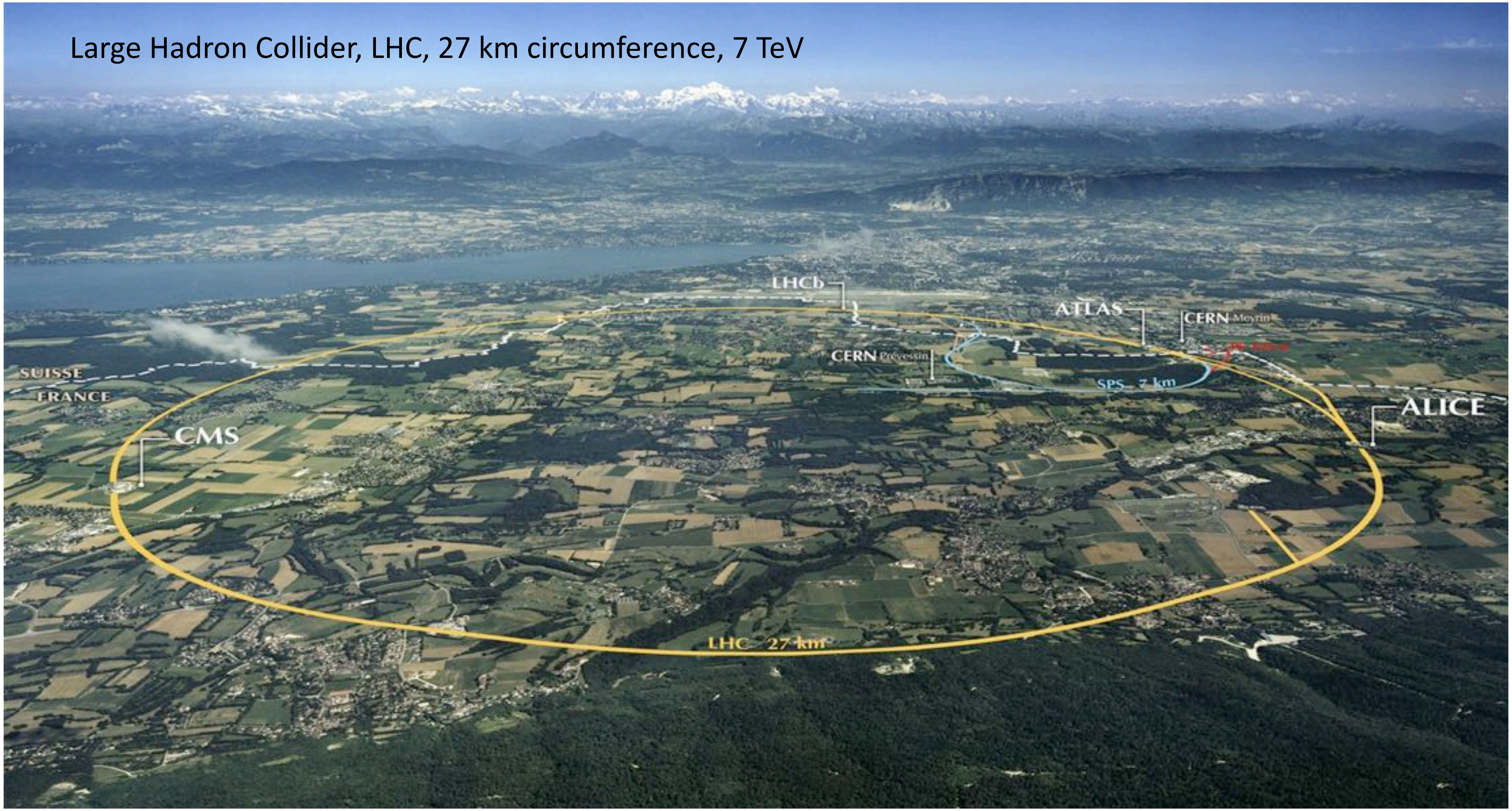
- **Need particle accelerators with new energy frontier**

➔ **30’000 accelerators worldwide!**

Also application of accelerators outside particle physics in medicine, material science, biology, etc…

LHC

Large Hadron Collider, LHC, 27 km circumference, 7 TeV



Circular Collider

Electron/positron colliders:
→ limited by synchrotron radiation

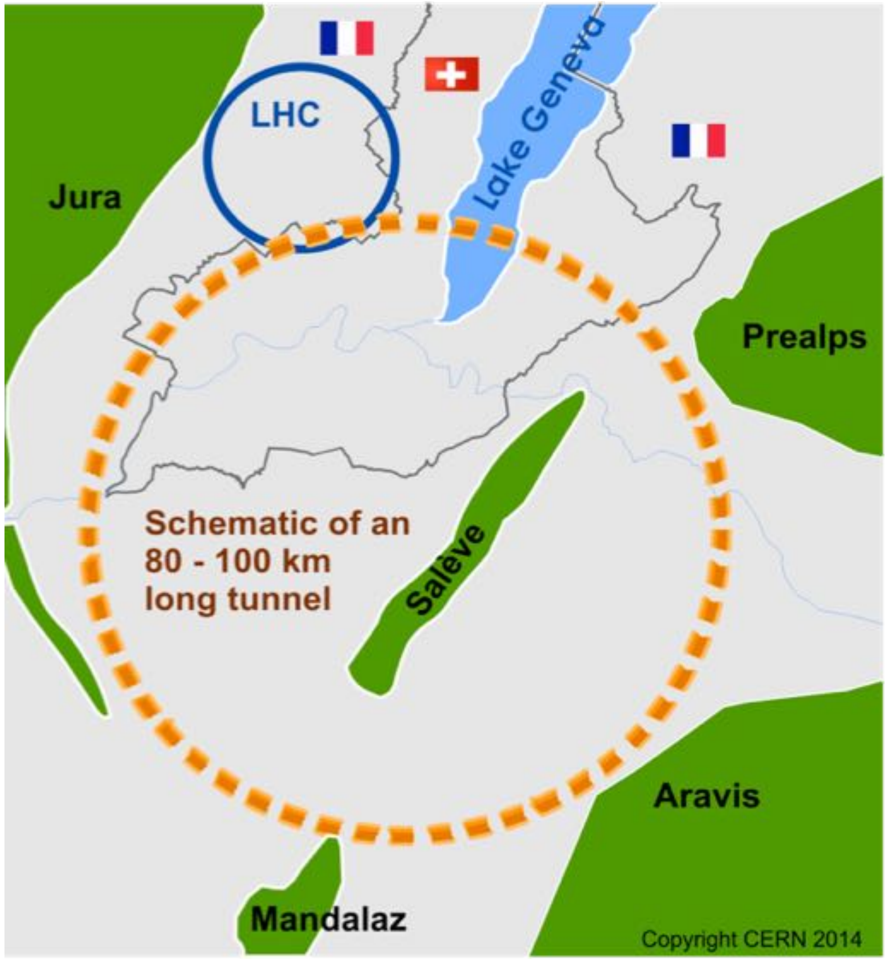
Hadron colliders:
→ limited by magnet strength

FCC, Future Circular Collider

80 – 100 km diameter

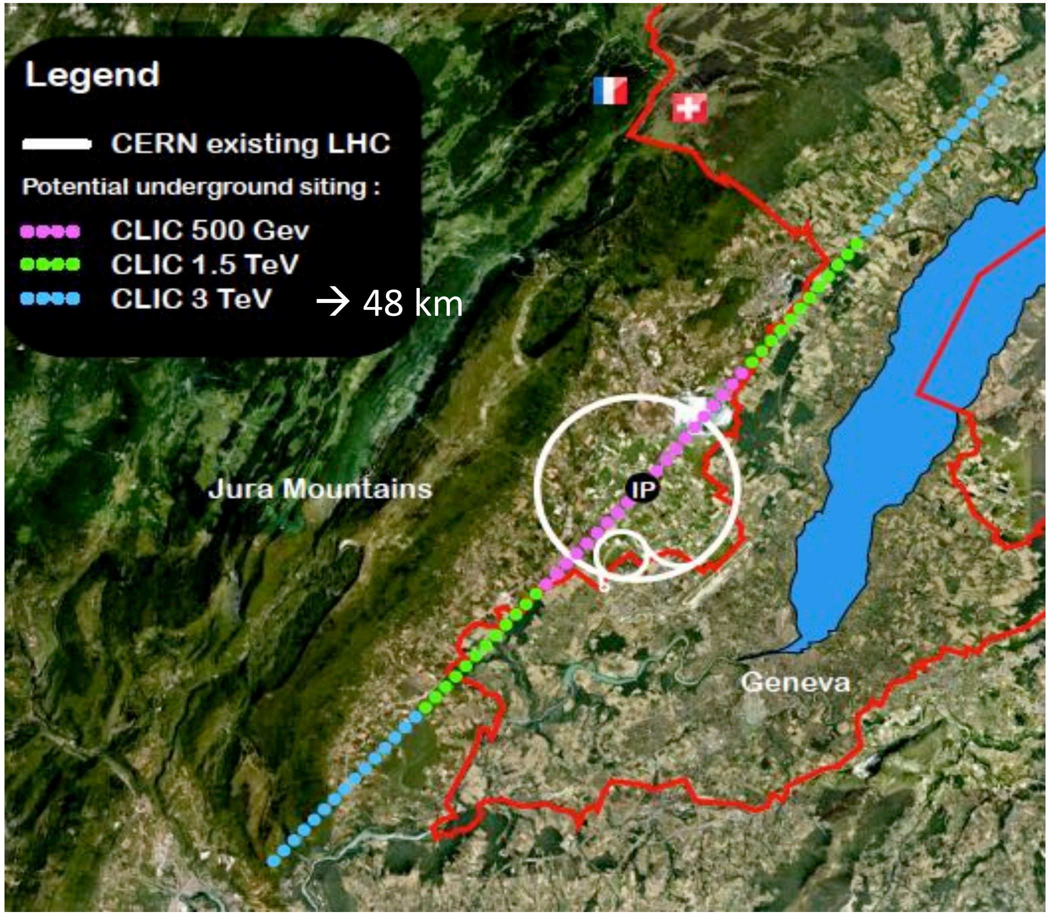
Electron/positron colliders:
→ 350 GeV

Hadron (pp) collider:
→ 100 TeV
→ → 20 T dipole magnets.



Linear Colliders

Particles are accelerated in a single pass.
Amount of acceleration achieved in a given distances is the ‘accelerating gradient’.
→ Limited by accelerating field.



CLIC

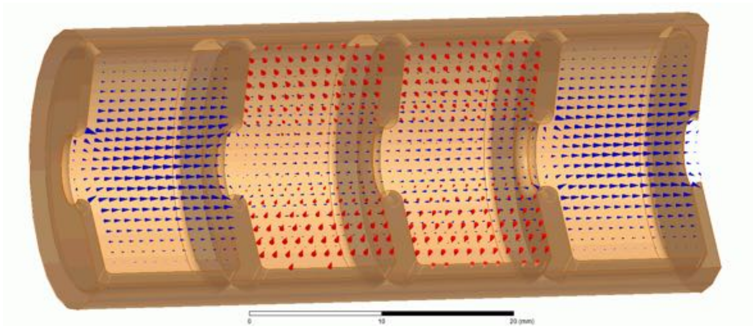
48 km length
3 TeV (e^+e^-)

Accelerating elements:
Cavities: 100 MV/m

Conventional Accelerating Technology

Today's RF cavities or microwave technology:

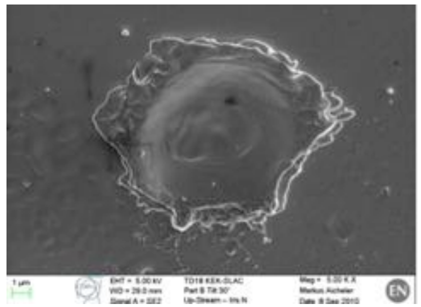
- Very successfully used in all accelerators (hospitals, scientific labs,...) in the last 100 years.



- Typical gradients:
  - LHC: 5 MV/m
  - ILC: 35 MV/m
  - CLIC: 100 MV/m

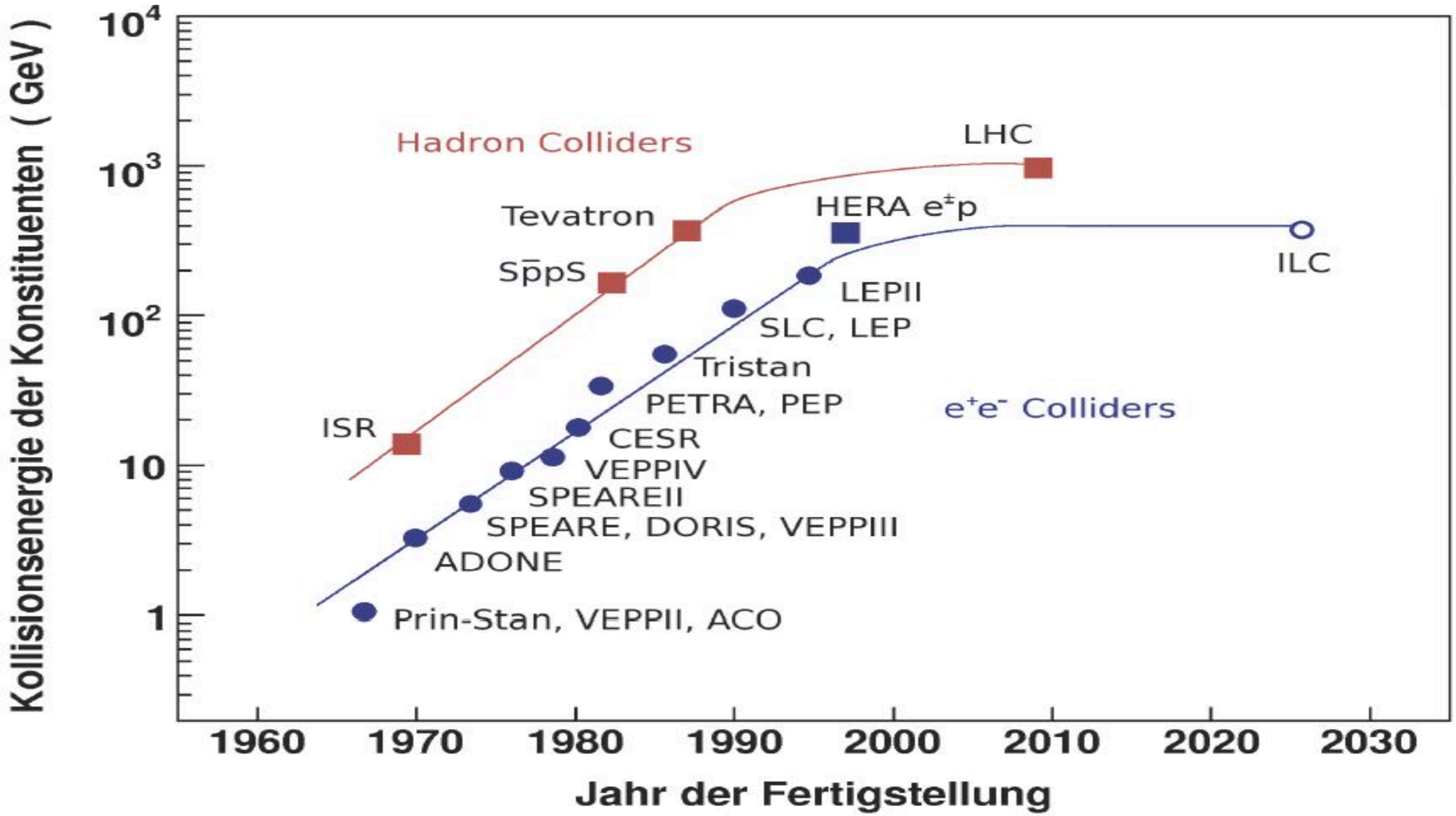
However:

- accelerating fields are limited to <100 MV/m
  - In metallic structures, a too high field level leads to break down of surfaces, creating electric discharge.
  - Fields cannot be sustained, structures might be damaged.



- several tens of kilometers for future linear colliders

Saturation at Energy Frontier for Accelerators



➔ **Project size and cost increase with energy**

Motivation

New directions in science are launched by new tools much more often than by new concepts.

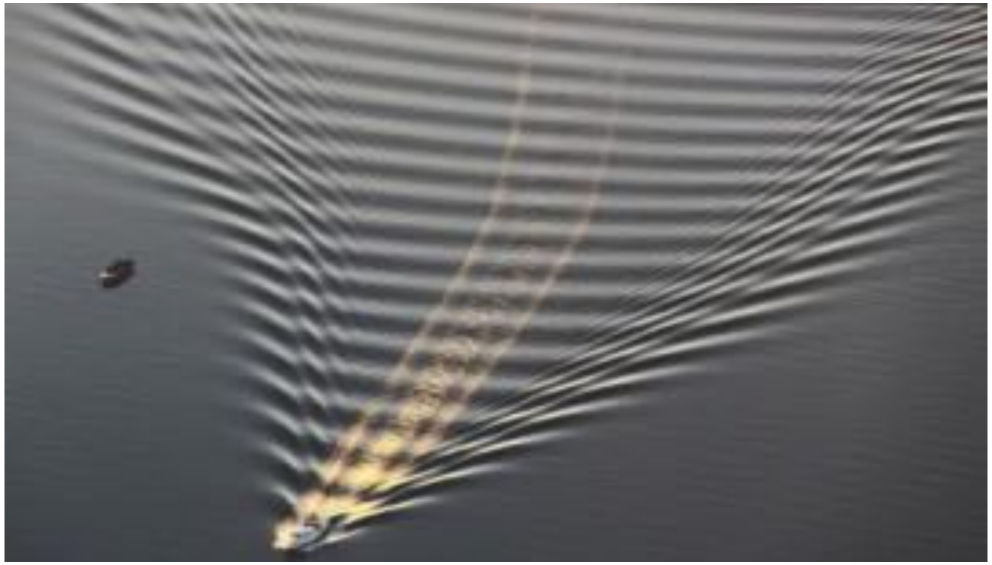
The effect of a concept-driven revolution is to explain old things in new ways.

The effect of a tool-driven revolution is to discover new things that have to be explained.

From Freeman Dyson ‘Imagined Worlds’

Plasma Wakefield Acceleration

Wakefield excitation

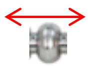


Particle acceleration

Cavities vs. Plasma

- ILC Cavity: 35 MV/m

- Plasma cell: 35 GV/m ➔ **35 MV/mm!!**

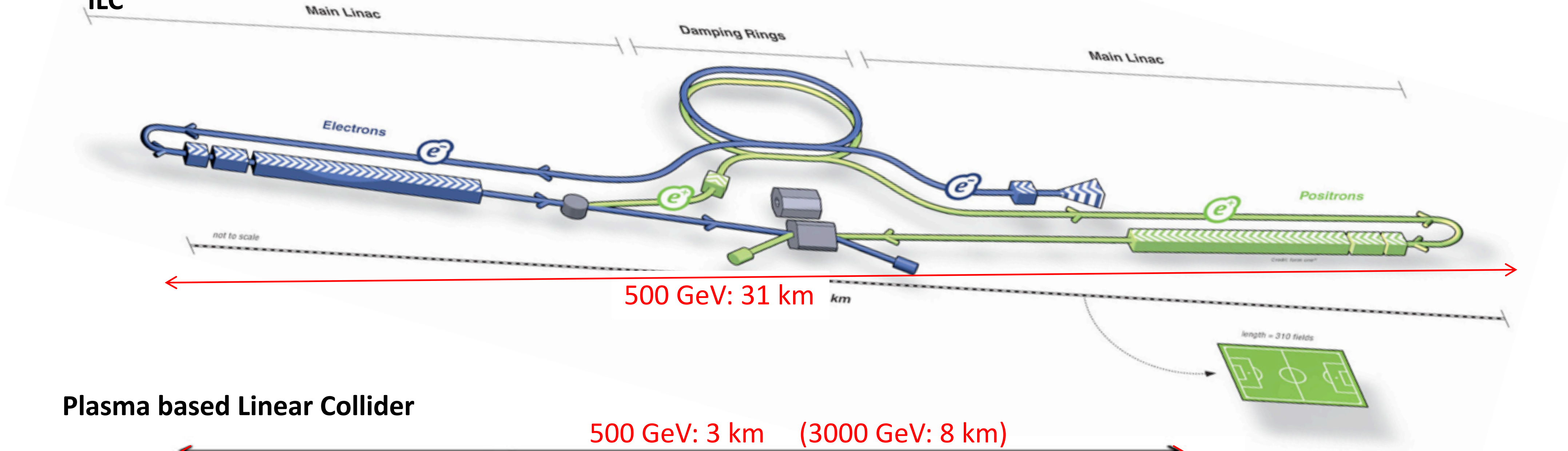


(Not to scale!)

With this new technology:
No magnets, no RF, no vacuum needed

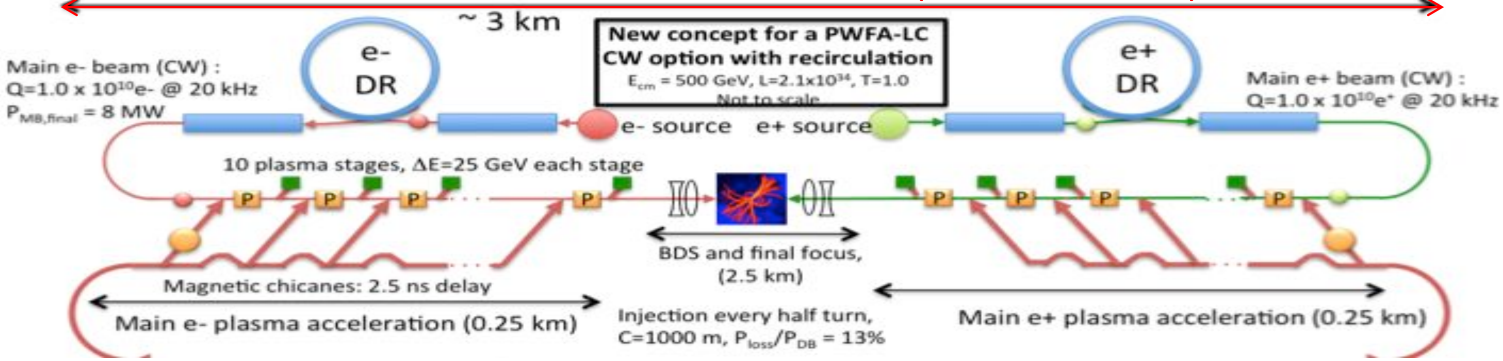
Linear Colliders

ILC



Plasma based Linear Collider

500 GeV: 3 km (3000 GeV: 8 km)



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Seminal Paper 1979, T. Tajima, J. Dawson

Use a plasma to convert the transverse space charge force of a beam driver into a longitudinal electrical field in the plasma

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Earlier Fermi[1] and McMillan[2] considered cosmic-ray particle acceleration by moving magnetic fields[1] or electromagnetic waves.[2] In terms of the realizable laboratory technology for collective accelerators, present-day electron beams[3] yield electric fields of $\sim 10^7$ V/cm and power densities of 10^{13} W/cm^2.

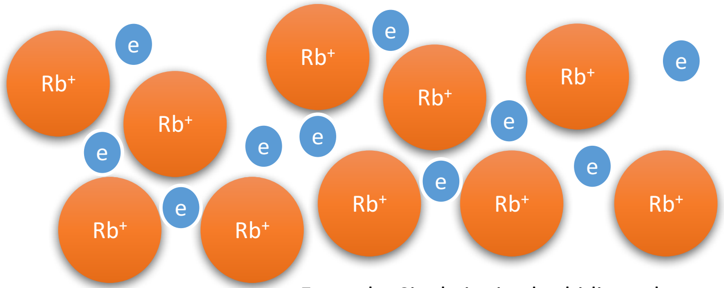
the wavelength of the plasma waves in the wake:

$$L_t = \lambda_w/2 = \pi c/\omega_p . \qquad (2)$$

An alternative way of exciting the plasmon is to inject two laser beams with slightly different frequencies (with frequency difference $\Delta\omega \sim \omega_p$) so that the beat distance of the packet becomes $2\pi c/\omega_p$. The mechanism for generating the wakes can be simply seen by the following approximate

Plasma Wakefield

What is a plasma?



Example: Single ionized rubidium plasma

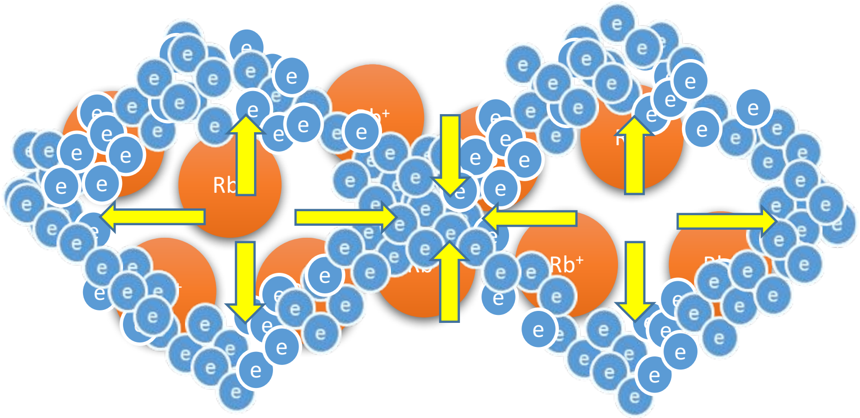
Plasma is already ionized or “broken-down” and can sustain **electric fields up to three orders of magnitude higher gradients** → order of **100 GV/m.**

Quasi-neutrality: the overall charge of a plasma is about zero.

Collective effects: Charged particles must be close enough together that each particle influences many nearby charged particles.

Electrostatic interactions dominate over collisions or ordinary gas kinetics.

What is a plasma wakefield?



Fields created by collective motion of plasma particles are called plasma wakefields.

Plasma Baseline Parameters

- A plasma of density n_{pe} is characterized by the plasma frequency

$$\omega_{pe} = \sqrt{\frac{n_{pe}\, e^2}{m_e\, \varepsilon_0}} \quad \rightarrow \quad \frac{c}{\omega_{pe}} \text{ ... unit of plasma [m]} \qquad k_{pe} = \frac{\omega_{pe}}{c}$$

Example: n_{pe} = 7×10^{14} cm^{-3} (AWAKE) → $\omega_{pe} = 1.25 \times 10^{12}$ rad/s → $\frac{c}{\omega_{pe}}$ **= 0.2mm** → $k_{pe} = 5$ mm^{-1}

- This translates into a wavelength of the plasma oscillation

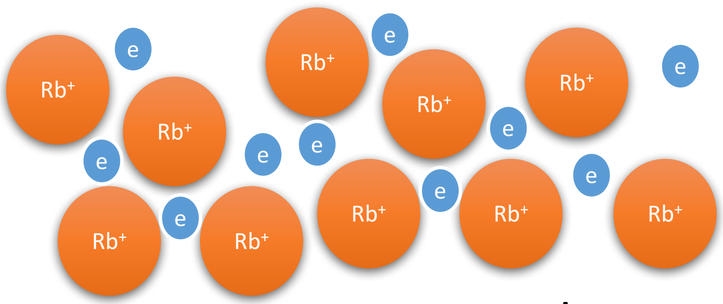
$$\lambda_{pe} = 2\pi \frac{c}{\omega_{pe}} \quad \rightarrow \quad \lambda_{pe} \approx 1\text{ mm} \sqrt{\frac{10^{15}\text{ cm}^{-3}}{n_{pe}}}$$

λ_{pe} = 1.2 mm → **Produce cavities with mm size!**

How to Create a Plasma Wakefield?

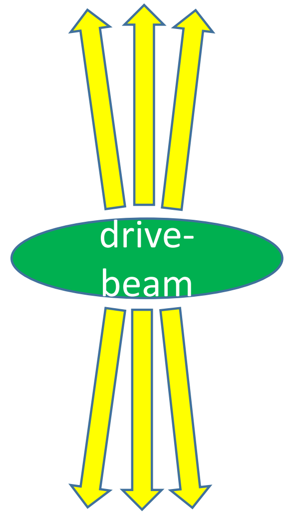
What we want:
Longitudinal electric field to accelerate charged particles.

Our Tool:



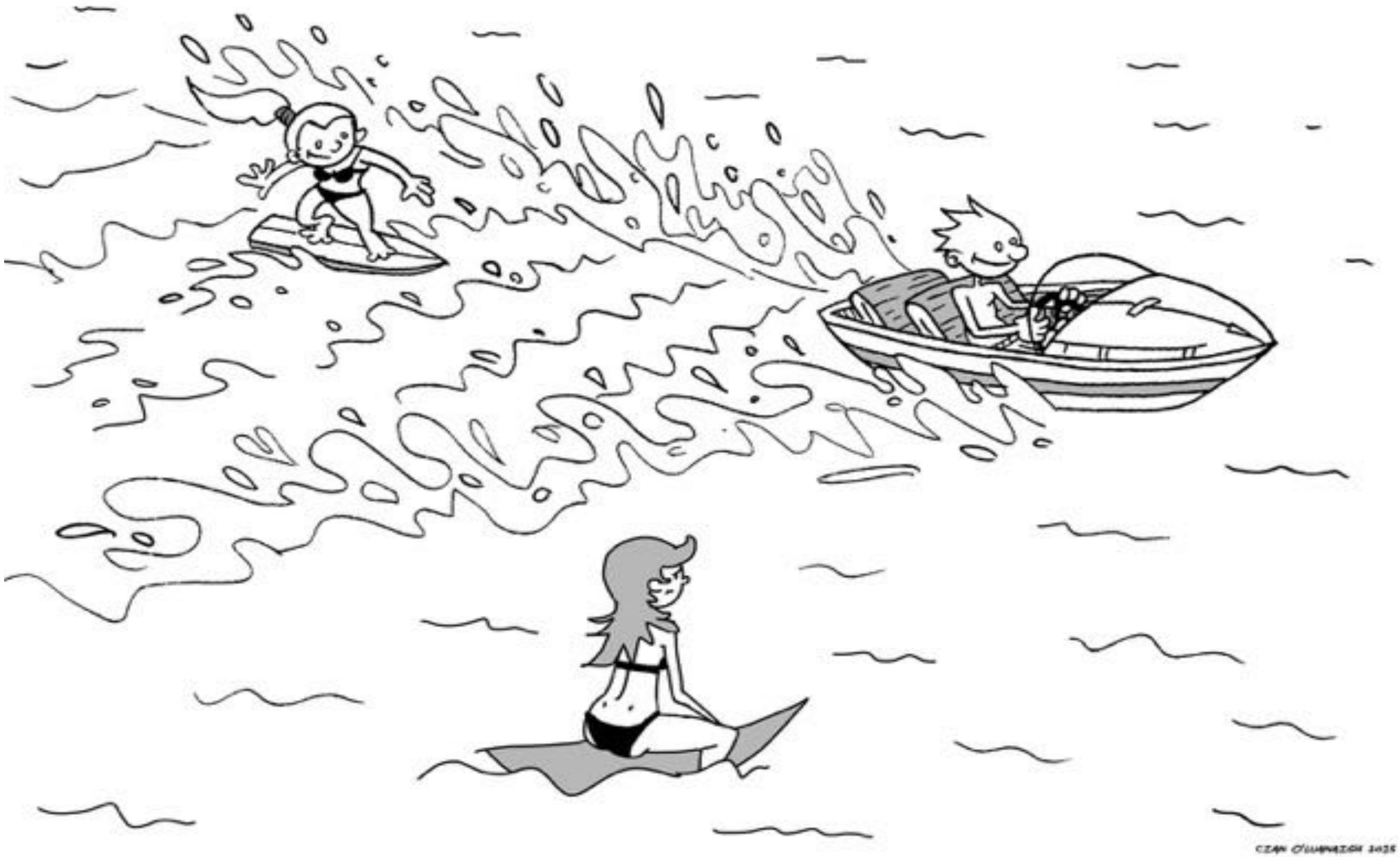
Single ionized rubidium **plasma**

Charged particle bunches carry almost purely transverse electric fields.



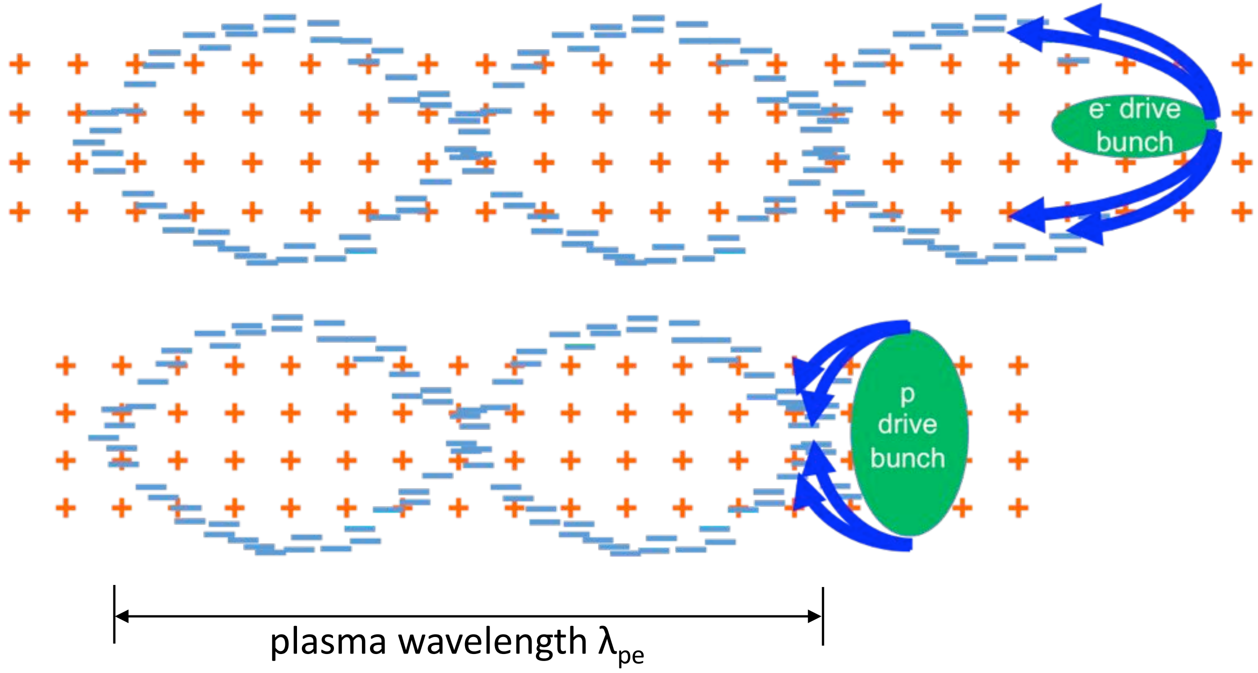
Using plasma to convert **the transverse electric field** of the drive bunch into a **longitudinal electric field in the plasma.** The more energy is available, the longer (distance-wise) these plasma wakefields can be driven.

How to Create a Plasma Wakefield?



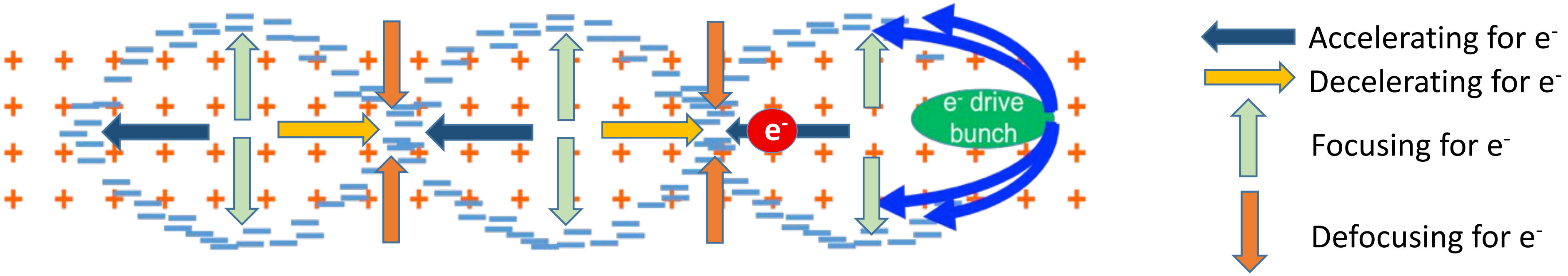
Principle of Plasma Wakefield Acceleration

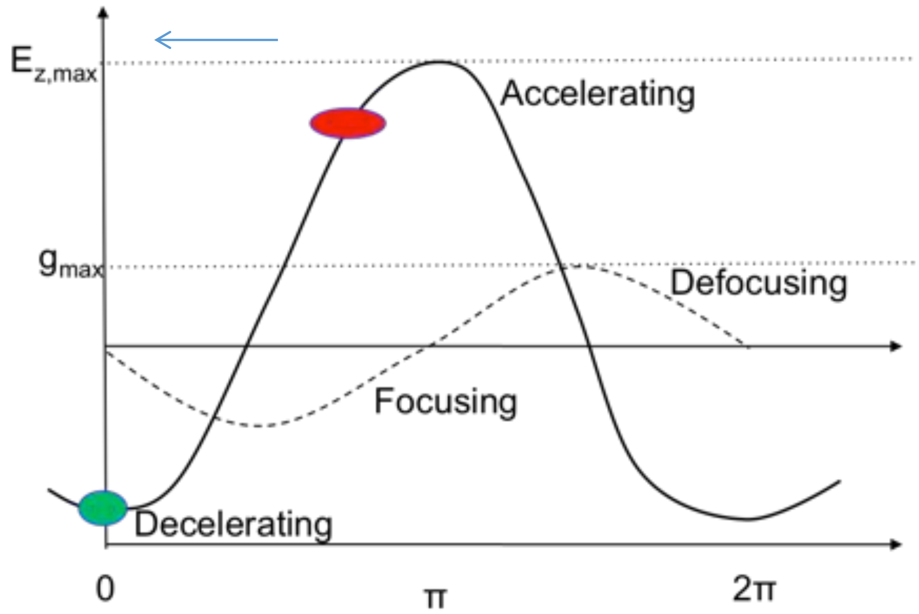
- **Laser drive beam**
  - ➔ Ponderomotive force
- **Charged particle drive beam**
  - ➔ Transverse space charge field
  - Reverses sign for negatively (blow-out) or positively (suck-in) charged beam



- Plasma wave/wake excited by relativistic particle bunch
- Plasma e^- are expelled by space charge force
- Plasma e^- rush back on axis
- Ultra-relativistic driver – ultra-relativistic wake → no dephasing
- Acceleration physics identical for LWFA, PWFA

Where to Place the Witness Beam (Surfer)?





Linear Theory (P. Chen, R. Ruth 1986)

When drive beam density is smaller than plasma density (n_b << n_p) → **linear theory.**

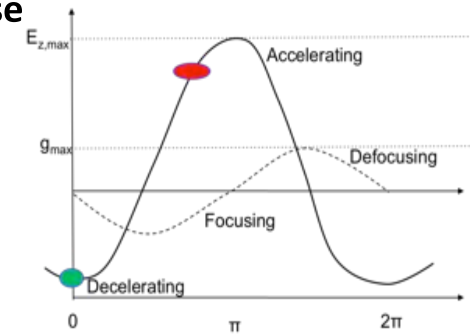
- Peak accelerating field in plasma resulting from drive beam with Gaussian distribution:

$$eE_z = \sqrt{n_p}\,\frac{n_b}{n_p}\,\frac{\sqrt{2\pi}\,k_p\sigma_z e^{-k_p^2\sigma_z^2/2}}{1+\frac{1}{k_p^2\sigma_r^2}}\sin k_p(z-ct) \quad (eV/cm)$$

➔ $eE_z \approx N/\sigma_z^2$

B.E. Blue 2003

- **Wakefield** excited by bunch oscillates **sinusoidally** with frequency determined by plasma density
- Fields excited by electrons and protons/positrons are **equal in magnitude but opposite in phase**



- The **accelerating field is maximized** for a value of

$$k_{pe}\,\sigma_z \approx \sqrt{2}$$
$$k_{pe}\,\sigma_r \leq 1$$

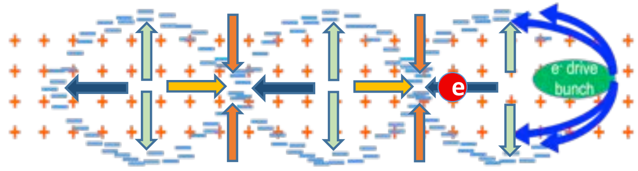
Example: n_{pe} = 7x10^{14} cm^{-3} (AWAKE), k_{pe} = 5 mm^{-1} ➔ **drive beam: σ_z = 300µm, σ_r = 200µm**

Linear Theory

- Maximum accelerating electric field reached with drive beam of N and σ_z:

$$E_{acc} = 110 \frac{\text{MV}}{\text{m}} \frac{N/(2 \times 10^{10})}{(\sigma_z / 0.6\text{mm})^2}$$

Drive beam fulfills: $k_{pe}\, \sigma_z \approx \sqrt{2}$



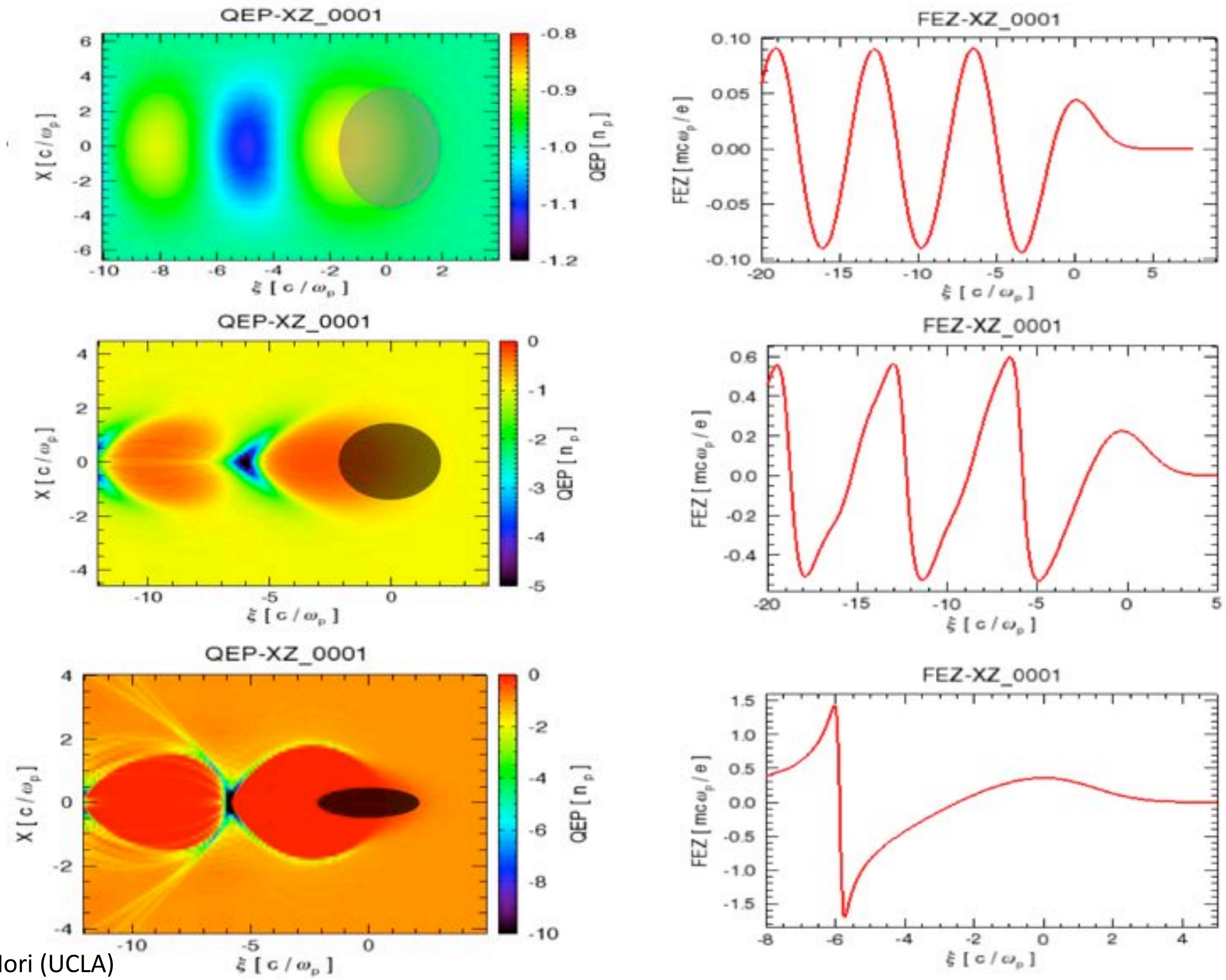
Examples of accelerating fields for different beam parameters and plasma parameters fields:

$N = 3\text{x}10^{10}$, $\sigma_z = 300\mu\text{m}$, $n_{pe} = 7\text{x}10^{14}\ \text{cm}^{-3}$ ➔ **E_{acc} = 600 MV/m**
$N = 3\text{x}10^{10}$, $\sigma_z = 20\mu\text{m}$, $n_{pe} = 2\text{x}10^{17}\ \text{cm}^{-3}$ ➔ **E_{acc} = 15 GV/m**

From Linear to Non-Linear

Electron density

Longitudinal fields



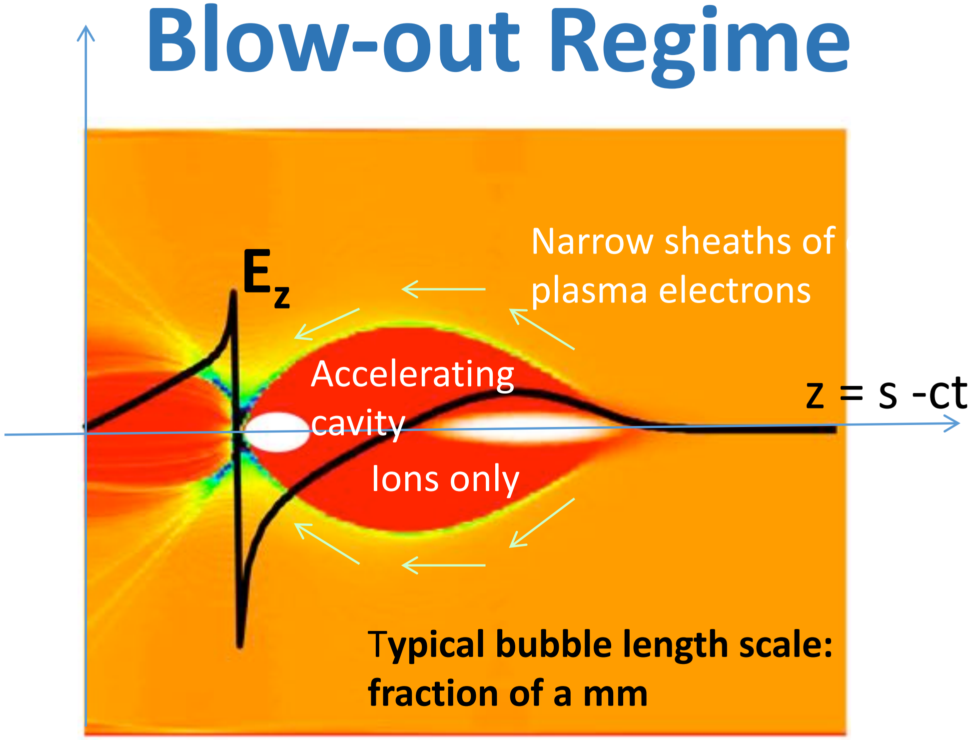
$n_b << n_{pe}$ – linear regime

$n_b \sim n_{pe}$ – non-linear wakes

$n_b >> n_{pe}$ – **blow-out regime**

W. Mori (UCLA)

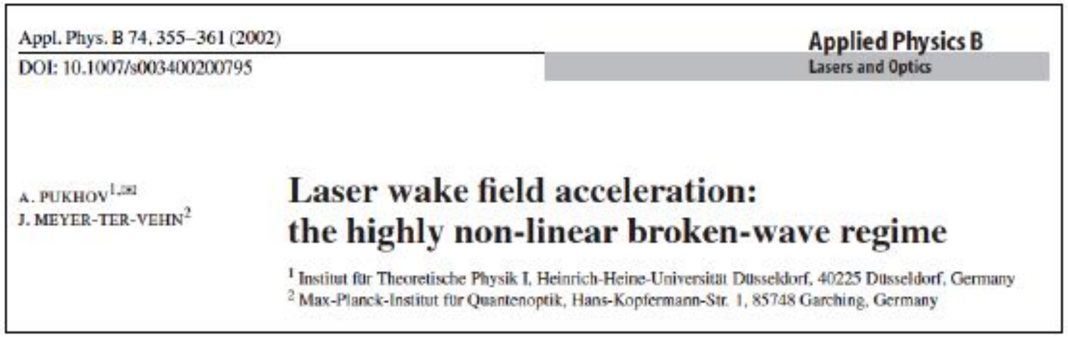
Blow-out Regime



- **Space-charge force** of the driver blows away **all the plasma electrons** in its path, leaving a uniform layer of ions behind (ions move on a slower time scale).
- Plasma electrons form a **narrow sheath** around the evacuated area, and are **pulled back by the ion-channel** after the drive beam has passed
- An **accelerating cavity** is formed in the plasma
- The back of the blown-out region: **ideal for electron acceleration**

→ **High efficiencies** for energy transfer from drive beam to loaded witness bunch (80-90% according to sim.)
→ **High charge witness** acceleration possible → charge ratio to witness of same order
→ **Linear focusing in r**, for electrons; very strong quadrupole (MT/m)
→ **High transformer ratios (>2)** can be achieved by shaping the drive bunch
→ **E_r independent of x**, can **preserve incoming emittance** of witness beam

Self-Injection Scheme

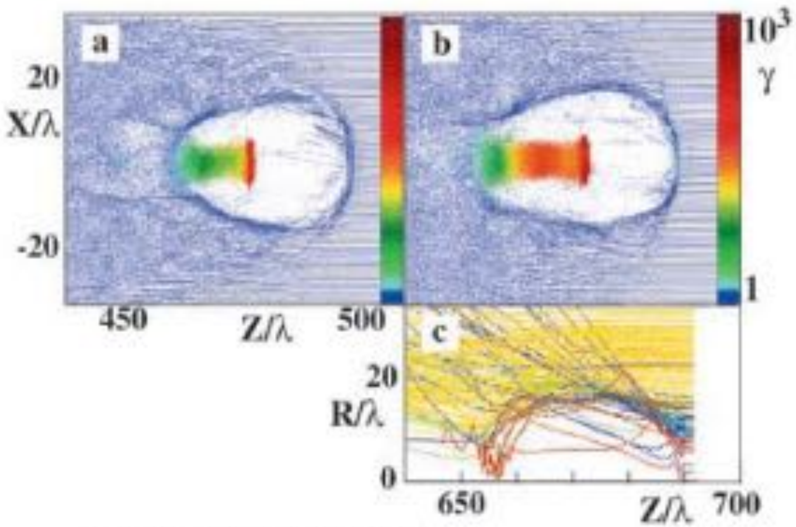


Appl. Phys. B 74, 355–361 (2002)
DOI: 10.1007/s003400200795
Applied Physics B
Lasers and Optics

A. PUKHOV[1,✉]
J. MEYER-TER-VEHN[2]

Laser wake field acceleration: the highly non-linear broken-wave regime

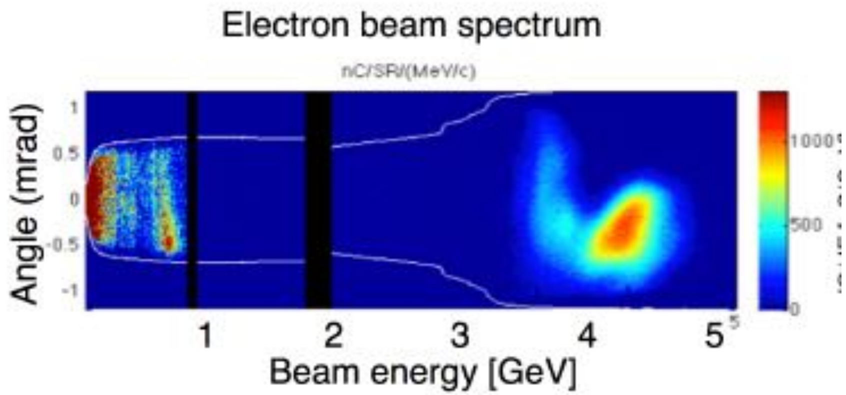
[1] Institut für Theoretische Physik I, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany
[2] Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany



Pukhov, ter-Vehn 2002

4.25 GeV beams obtained from 9cm plasma channel powered by 310TW laser pulse (15 J)

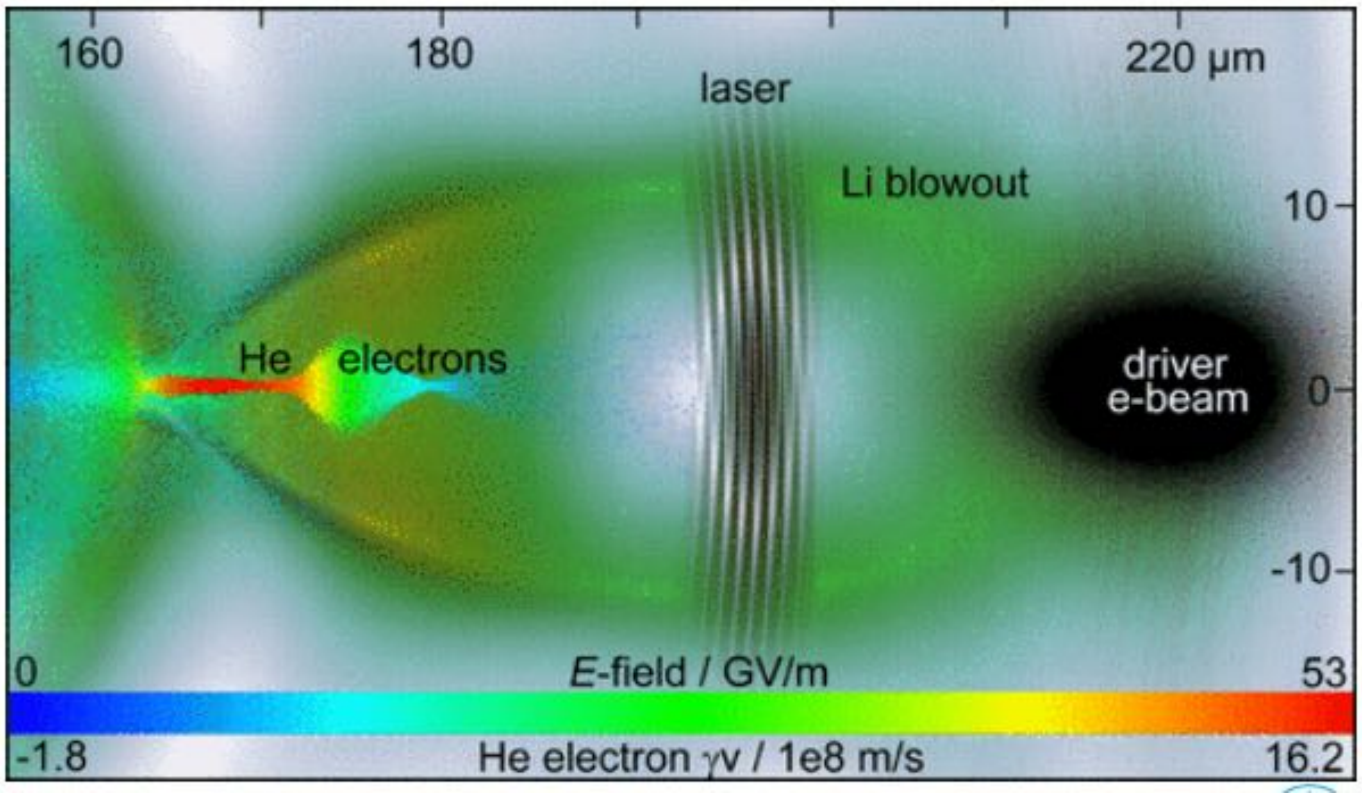
W.P.Leemans et al., PRL 2014



Hybrid Scheme

- **Beam-driven** plasma wakefield using low-ionization-threshold gas such as **Li**
- **Laser-controlled** electron injection via ionization of high-ionization threshold gas such as **He**

B. Hidding et al., PRL 108, 035001 (2012)



Ultra-high brightness beams:

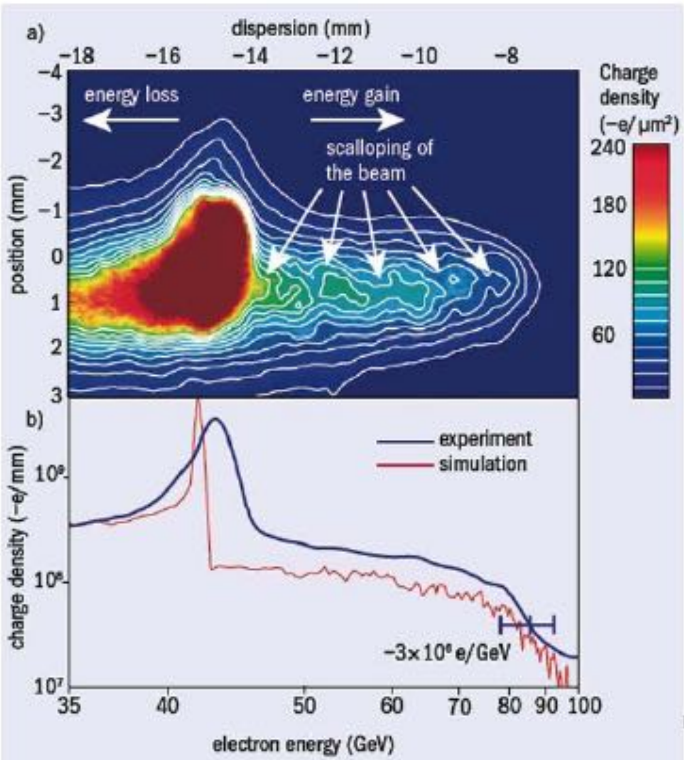
- Sub-µm spot size
- fs pulses
- Small emittance

He-electrons with low transverse momentum released in focus of laser, inside accelerating and focusing phase of the Li blowout

Experimental Results

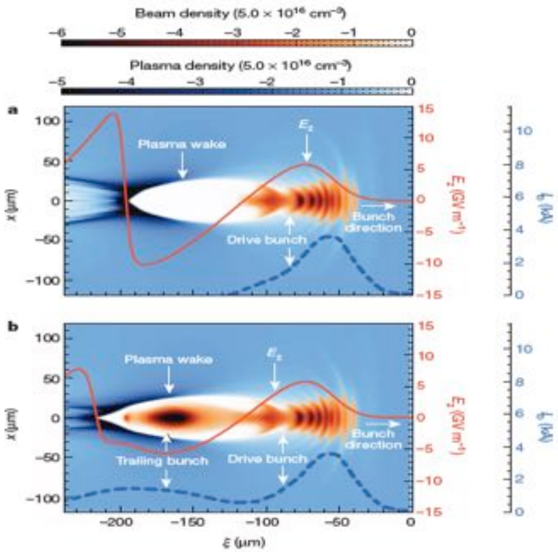
SLAC Experiment, I. Blumenfeld et al, Nature 455, p 741 (2007)

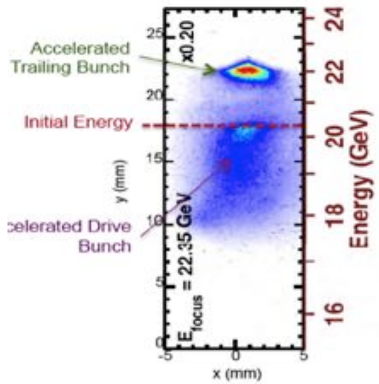
- Gaussian electron beam with 42 GeV, 3nC @ 10 Hz, σ_x = 10µm, 50 fs
- Reached accelerating gradient of 50 GeV/m
- Accelerated electrons from 42 GeV to 85 GeV in 85 cm.



High-Efficiency acceleration of an electron beam in a plasma wakefield accelerator, M. Litos et al., doi, Nature, 6 Nov 2014, 10.1038/nature 13992

- 1.7 GeV energy gain in 30 cm of pre-ionized Li vapour plasma
- 6 GeV energy in 1.3 m of plasma
- Total efficiency is <29.1%> with a maximum of 50%.
- Final energy spread of 0.7 % (2% average)





- Electric field in plasma wake is loaded by presence of witness bunch
- Allows efficient energy extraction from the plasma wake

Many, Many Electron and Laser Driven Plasma Wakefield Experiments…!

Now first Proton Driven Plasma Wakefield Experiment

Beam-Driven Wakefield Acceleration: Landscape

Facility	Where	Drive (D) beam	Witness (W) beam	Start	End	Goal
AWAKE	CERN, Geneva, Switzerland	400 GeV **protons**	Externally injected electron beam (PHIN 15 MeV)	2016	2020+	**Use for future high energy e-/e+ collider.** - Study Self-Modulation Instability (SMI). - Accelerate externally injected electrons. - Demonstrate scalability of acceleration scheme.
SLAC-FACET	SLAC, Stanford, USA	20 GeV **electrons** and **positrons**	Two-bunch formed with mask (e^-/e^+ and e^--e^+ bunches)	2012	Sept 2016	- Acceleration of witness bunch with high **quality and efficiency** - Acceleration of positrons - FACET II preparation, starting 2018
DESY-Zeuthen	PITZ, DESY, Zeuthen, Germany	20 MeV **electron** beam	No witness (W) beam, only D beam from RF-gun.	2015	~2017	- Study Self-Modulation Instability **(SMI)**
DESY-FLASH Forward	DESY, Hamburg, Germany	X-ray FEL type **electron** beam 1 GeV	D + W in FEL bunch. Or independent W-bunch (LWFA).	2016	2020+	- **Application (mostly) for x-ray FEL** - Energy-doubling of Flash-beam energy - Upgrade-stage: use 2 GeV FEL D beam
Brookhaven ATF	BNL, Brookhaven, USA	60 MeV **electrons**	Several bunches, D+W formed with mask.	On going		- **Study quasi-nonlinear PWFA regime.** - Study PWFA driven by multiple bunches - Visualisation with optical techniques
SPARC Lab	Frascati, Italy	150 MeV	Several bunches	On going		- Multi-purpose user facility: includes laser- and beam-driven plasma wakefield experiments

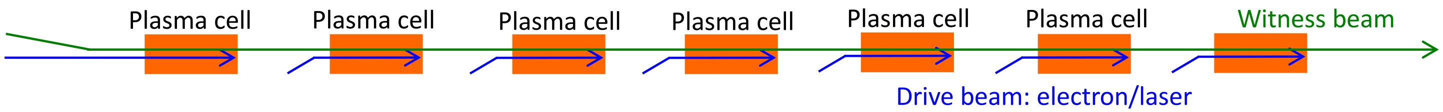
High Energy Plasma Wakefield Accelerators

Drive beams:
Lasers: ~40 J/pulse
Electron drive beam: 30 J/bunch
Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

Witness beams:
Electrons: 10^{10} particles @ 1 TeV ~few kJ

To reach TeV scale:

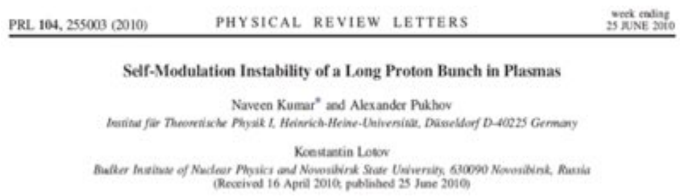
- **Electron/laser driven PWA**: need several stages, and challenging wrt to relative timing, tolerances, matching, etc…
  - effective gradient reduced because of long sections between accelerating elements….



- **Proton drivers**: large energy content in proton bunches → allows to consider single stage acceleration:
  - A single SPS/LHC bunch could produce an ILC bunch in a single PDWA stage.

Self-Modulation Instability

- In order to create plasma wakefields efficiently, the drive bunch length has to be in the order of the plasma wavelength.
- **CERN SPS proton bunch: very long!**
- Longitudinal beam size (**σ_z = 12 cm**) is much longer than plasma wavelength **(λ = 1mm)**

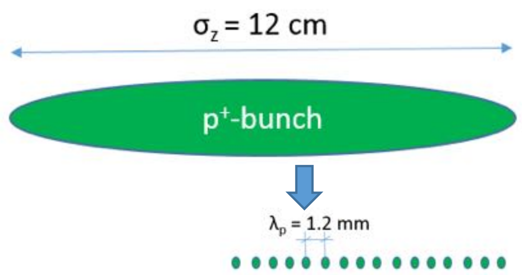

PRL 104, 255003 (2010) PHYSICAL REVIEW LETTERS week ending 25 JUNE 2010

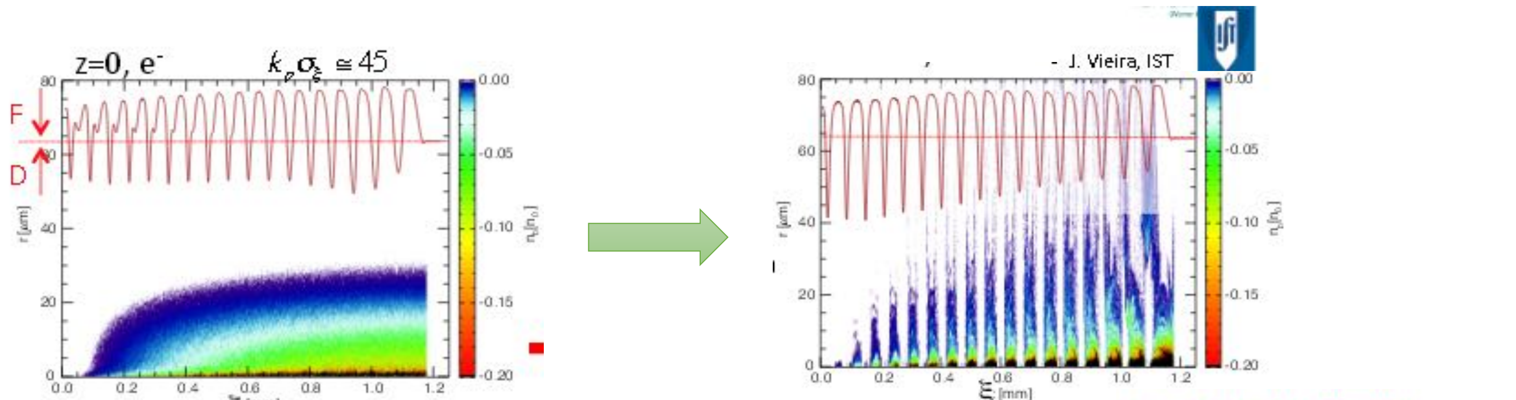
Self-Modulation Instability of a Long Proton Bunch in Plasmas

Naveen Kumar* and Alexander Pukhov
Institut für Theoretische Physik I, Heinrich-Heine-Universität, Düsseldorf D-40225 Germany
Konstantin Lotov
Budker Institute of Nuclear Physics and Novosibirsk State University, 630090 Novosibirsk, Russia
(Received 16 April 2010; published 25 June 2010)

Self-Modulation Instability

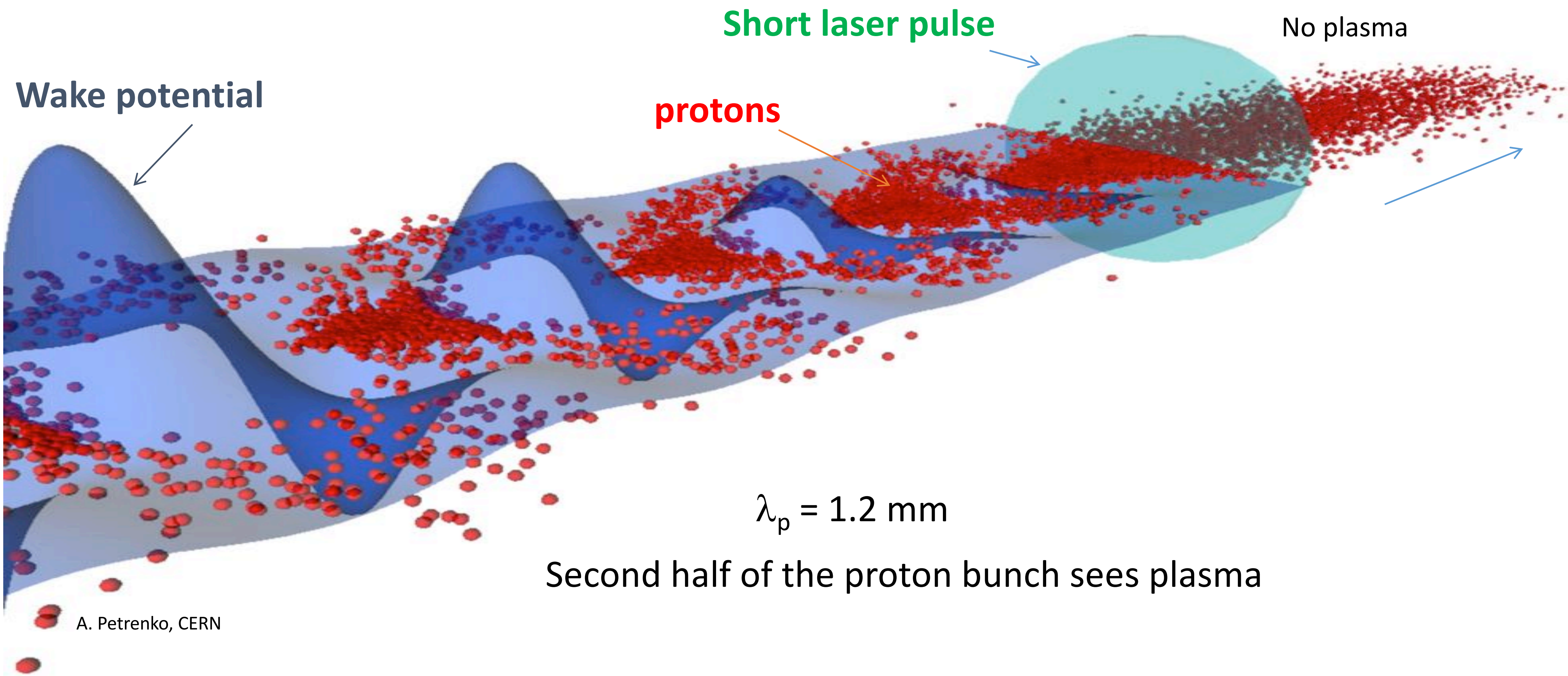
- Modulate long bunch to produce a series **of 'micro-bunches' in a plasma with a spacing of plasma wavelength λ_p.**
  - →Strong self-modulation effect of proton beam due to transverse wakefield in plasma
  - →**Resonantly drives the longitudinal wakefield**





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

Seeded Self-Modulation of a Long Proton Bunch in Plasma



λ_p = 1.2 mm

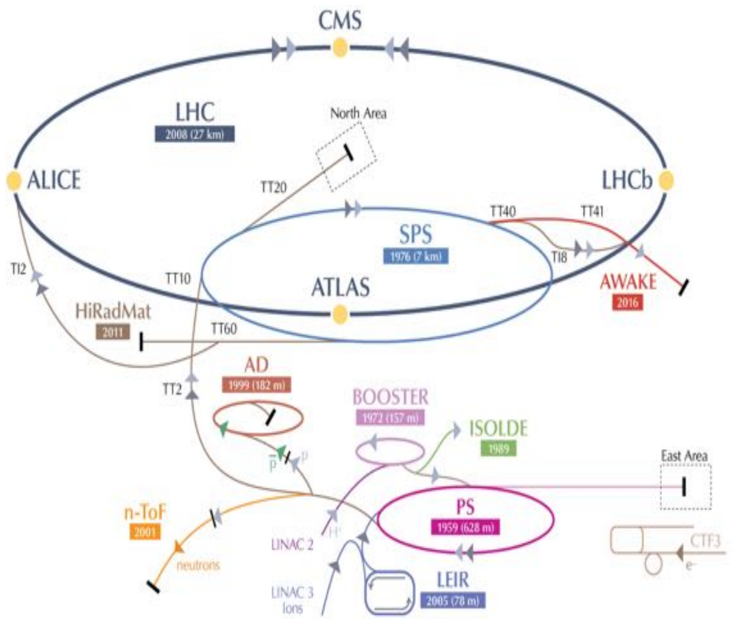
Second half of the proton bunch sees plasma

A. Petrenko, CERN

Outline

- Motivation
- Plasma Wakefield Acceleration
- AWAKE
- Outlook

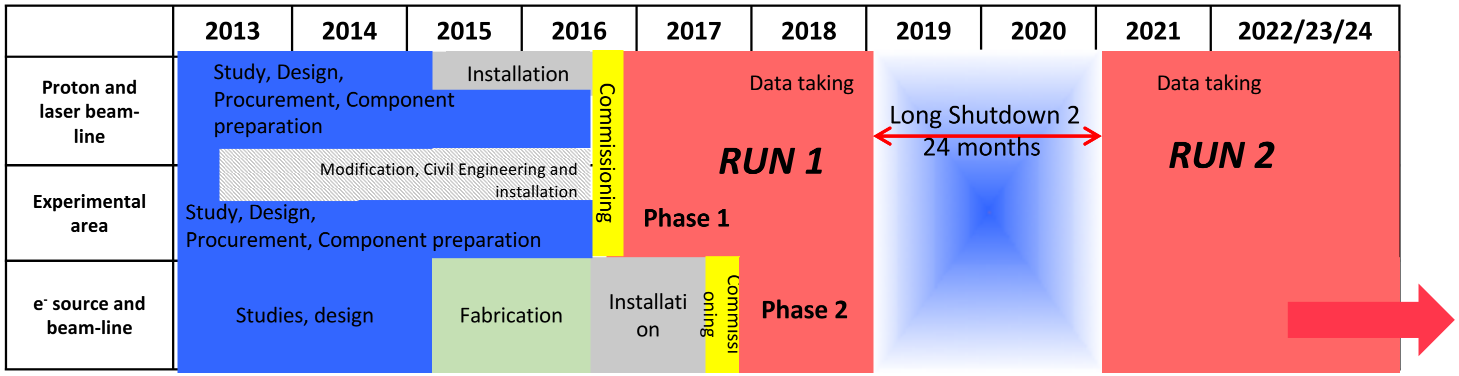
AWAKE at CERN



Advanced Proton Driven Plasma Wakefield Acceleration Experiment

- Proof-of-Principle Accelerator R&D experiment at CERN
- Final Goal: Design high quality & high energy electron accelerator based on acquired knowledge.
- AWAKE Collaboration: 16 institutes + 3 associate

- Approved in August 2013
- First beam end 2016

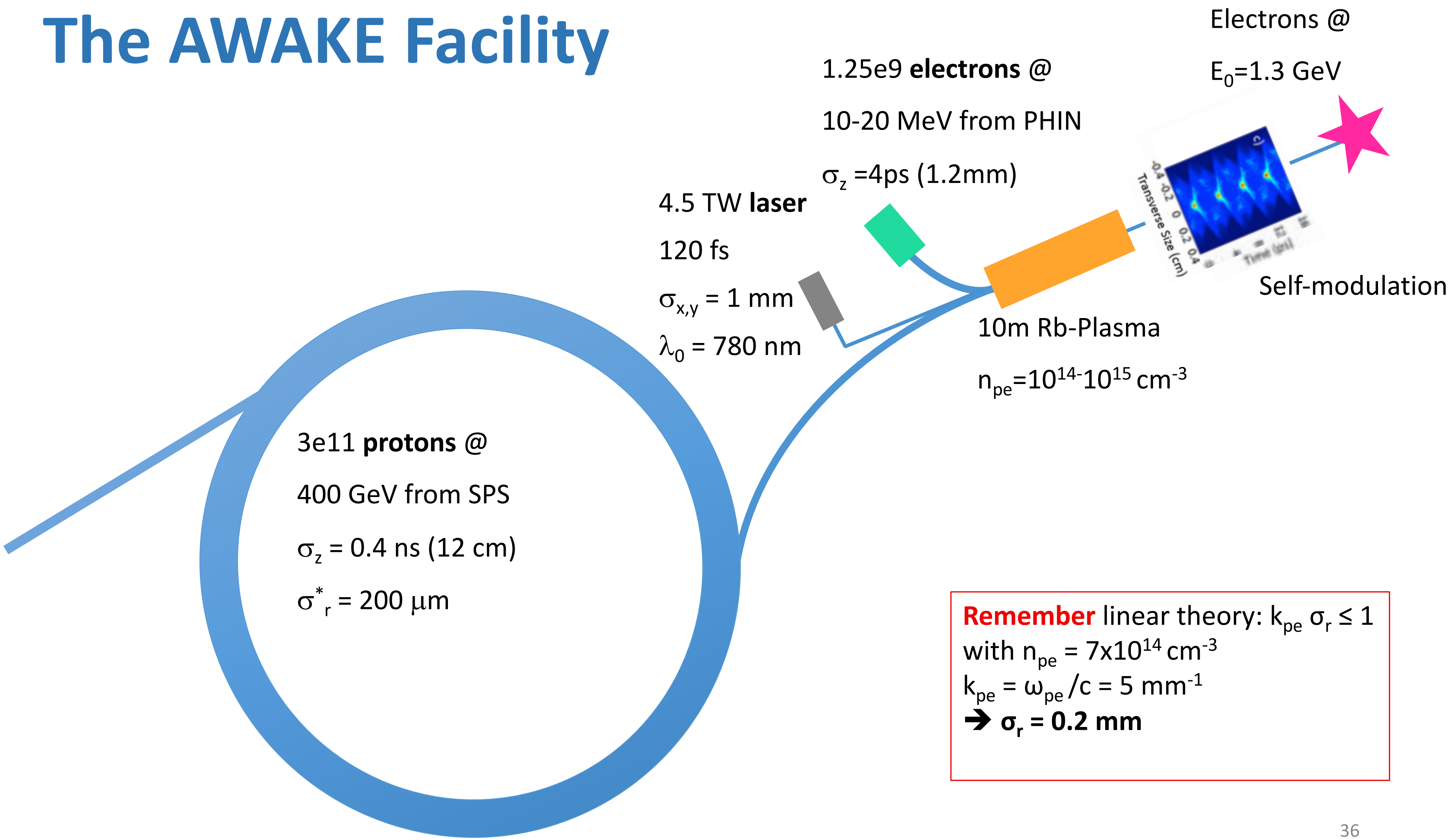


Run 1 – until LS2 of the LHC.

After LS2 – proposing Run 2 of AWAKE (during Run 3 of LHC)

After Run 2 – kick off particle physics driven applications

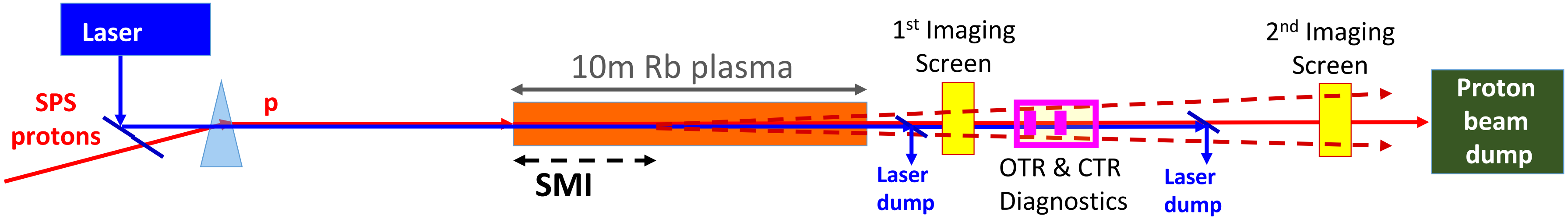
The AWAKE Facility



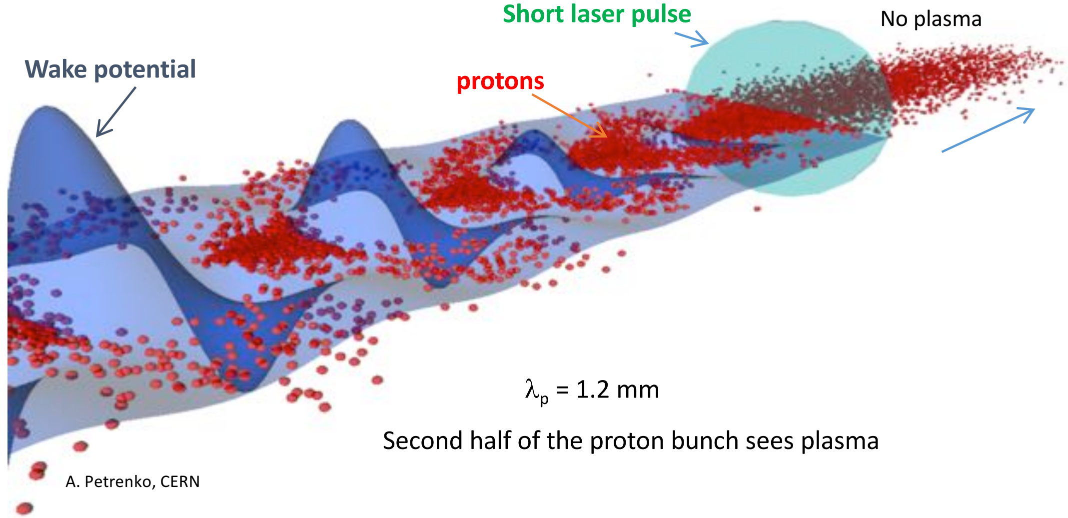
Remember linear theory: $k_{pe}\ \sigma_r \leq 1$
with $n_{pe} = 7\times10^{14}$ cm^{-3}
$k_{pe} = \omega_{pe}/c = 5$ mm^{-1}
➔ **σ_r = 0.2 mm**

First Experiment: Seeded Self-Modulation

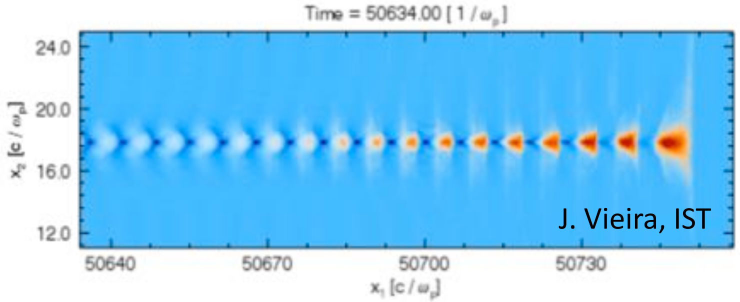
Phase 1: 2016/17: Understand **the physics of the seeded self-modulation** processes in plasma.



Self-modulated proton bunch resonantly driving plasma wakefields.

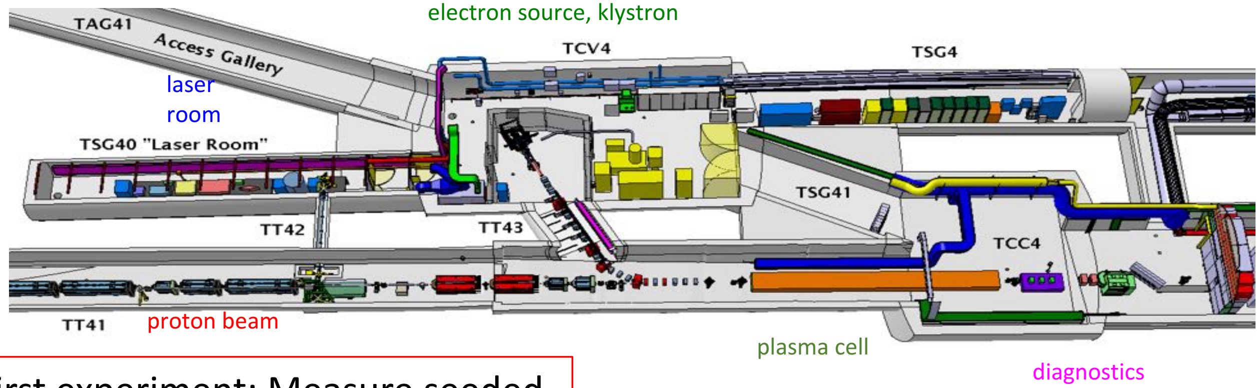


What we want to see in the diagnostics:

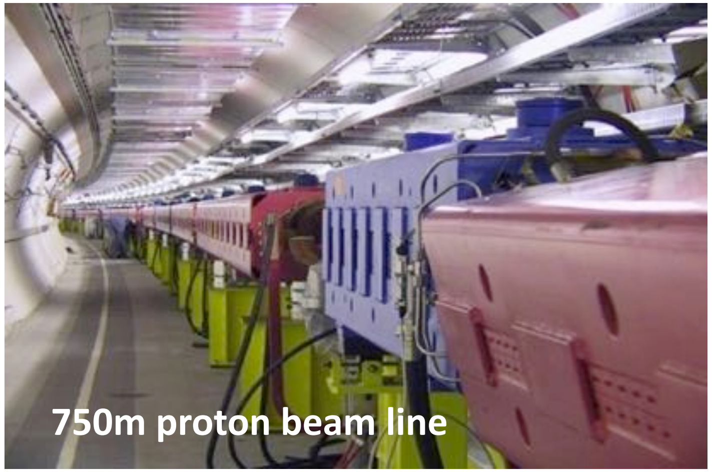


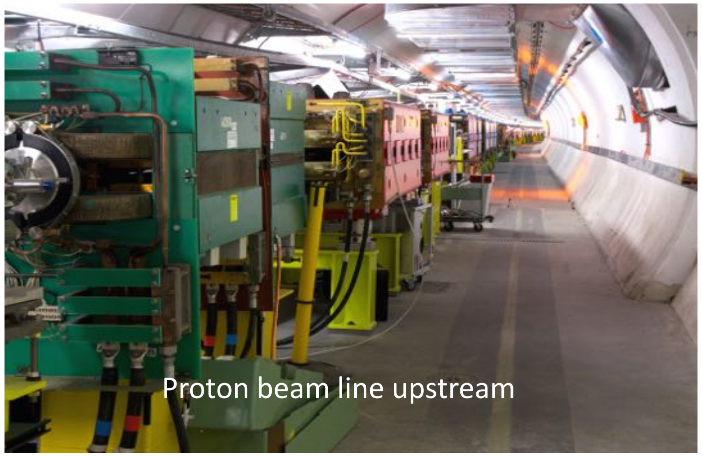
AWAKE Proton Beam Line

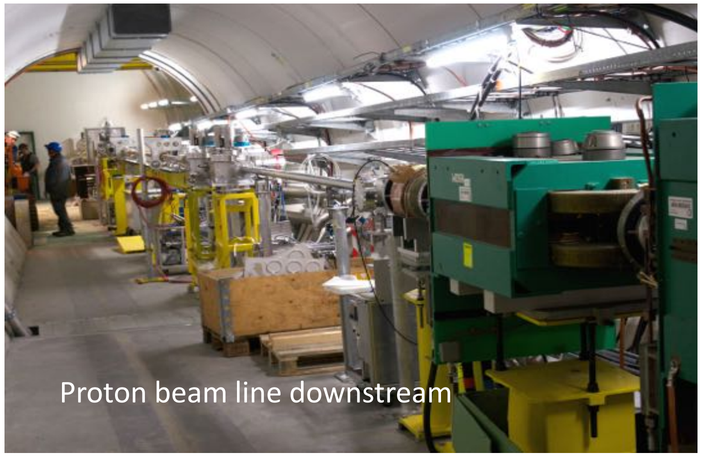
Parameter	Protons
Momentum [MeV/c]	400 000
Momentum spread [%]	±0.035
Particles per bunch	$3 \cdot 10^{11}$
Charge per bunch [nC]	48
Bunch length [mm]	120 (0.4 ns)
Norm. emittance [mm·mrad]	3.5
Repetition rate [Hz]	0.033
1σ spot size at focal point [μm]	200 ±20
β-function at focal point [m]	5
Dispersion at focal point [m]	0



First experiment: Measure seeded self-modulation!



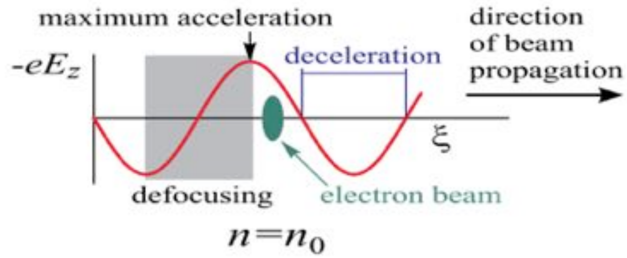




The AWAKE Plasma Cell

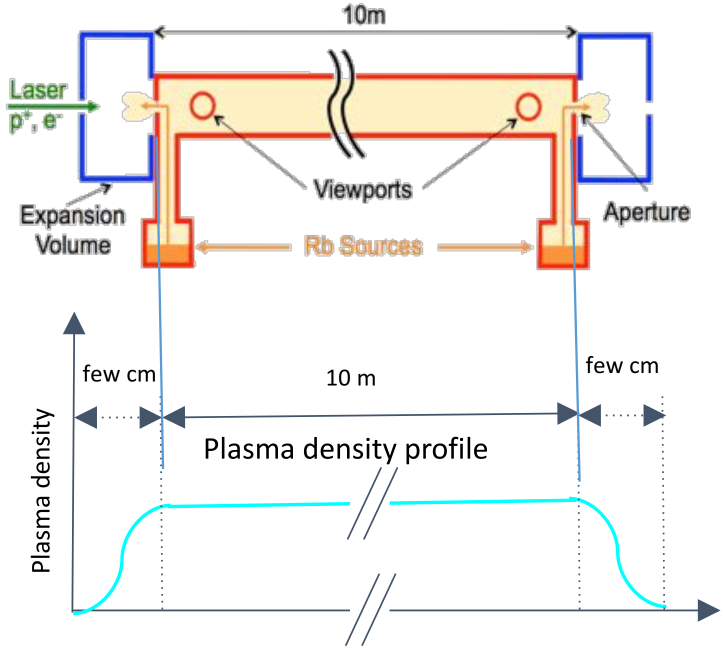
F. Batsch, F. Braunmueller, E. Oez, P. Muggli, (MPP, Munich)
R. Kerservan (CERN), G. Plyushchev (EPFL)

→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

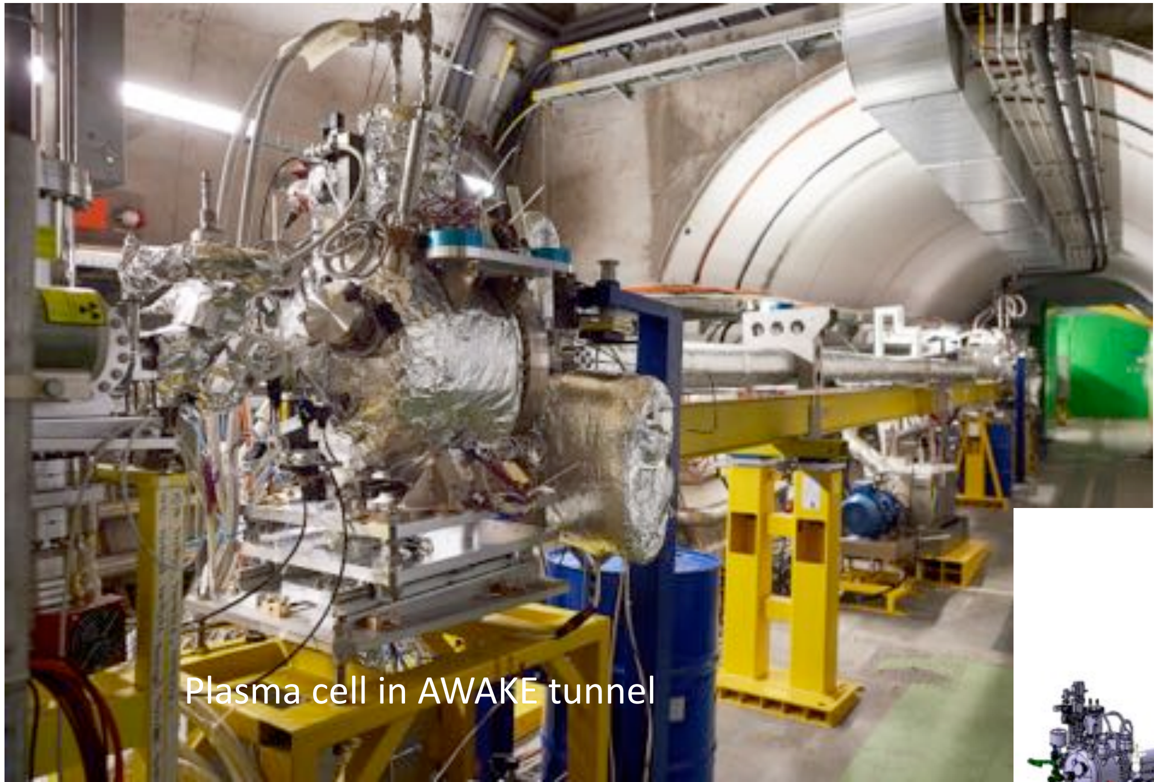


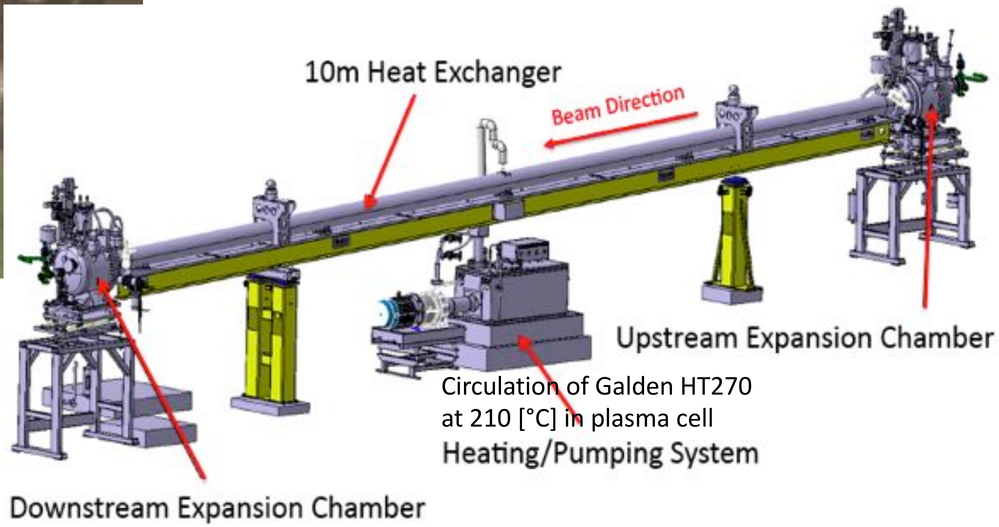
Requirements:

- 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%
    - Impose very uniform T: → Fluid-heated system (˜220 deg)
    - Complex control system: 79 Temperature probes, valves → measured $\Delta T/T$ ~0.1%
- few cm n_e ramp: transition between plasma and vacuum as sharp as possible
    - Rb vapor expands into vacuum and sticks to cold walls
    - Scale length ~ diameter aperture: 1cm



The AWAKE Plasma Cell



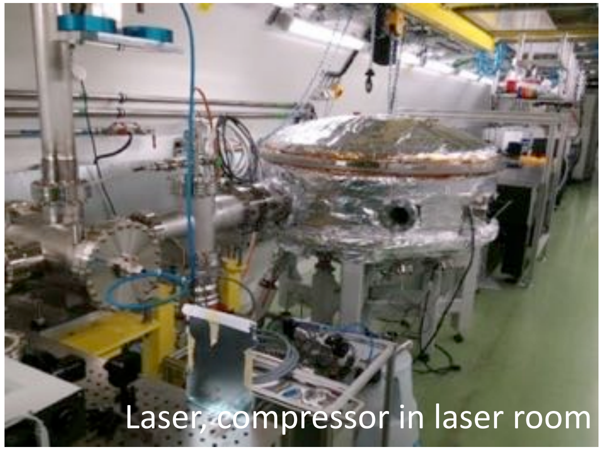


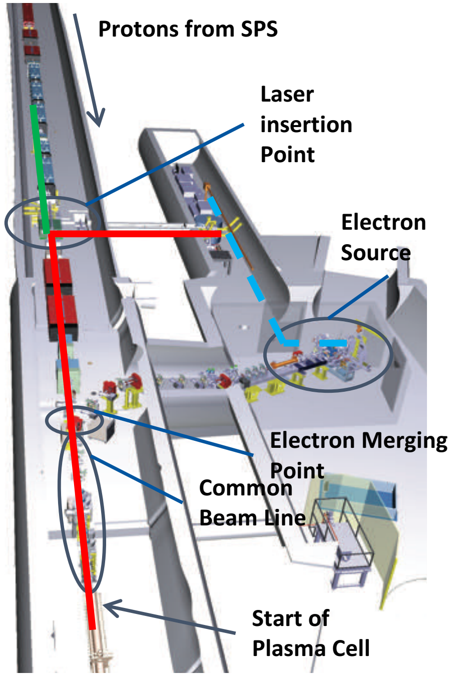
Laser and Laser Line

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

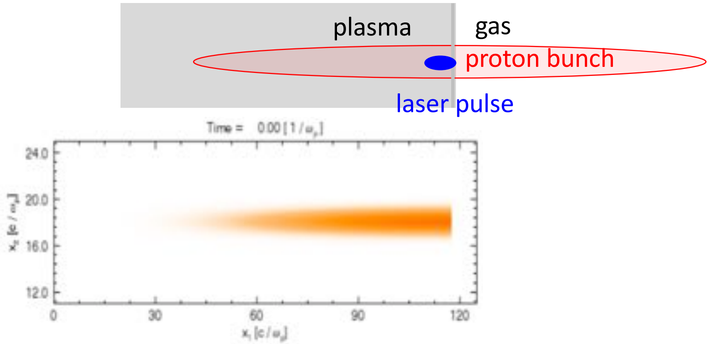
Fiber/Ti-Sapphire laser

- **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 (installed in 2017)*

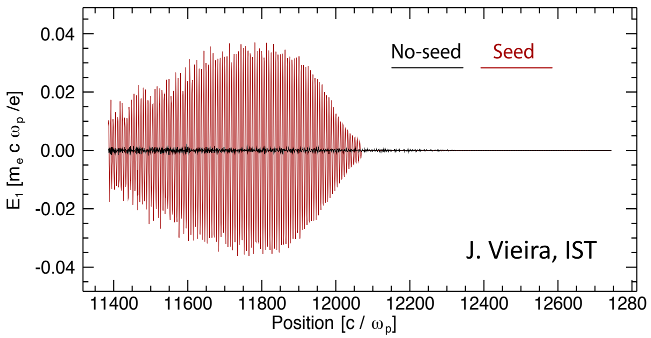




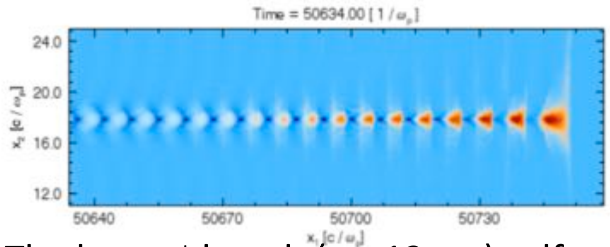
→ Short laser pulse creates the plasma, which seeds the self-modulation



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



No seed no SM (over 10m)

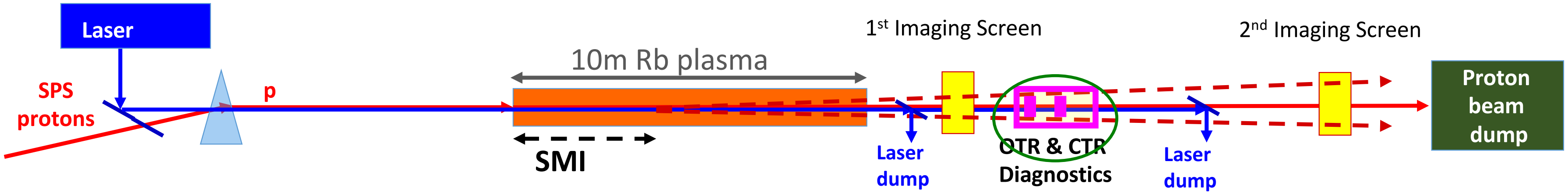


The long p^+ bunch (σ_z~12cm) self modulates with period λ_{pe}~1.2mm,
→ $100\lambda_{pe}$ per σ_z

Outline

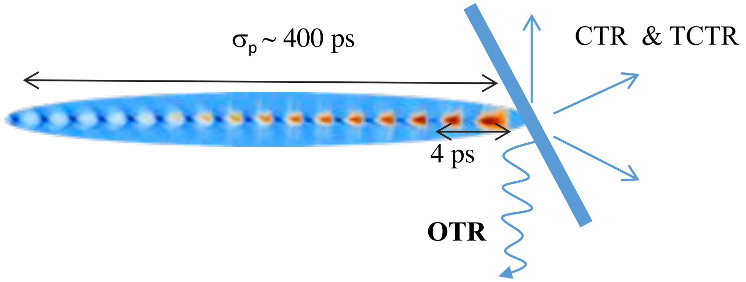
- Motivation
- Plasma Wakefield Acceleration
- AWAKE → First Results
- Outlook

Seeded Self-Modulation Diagnostics I



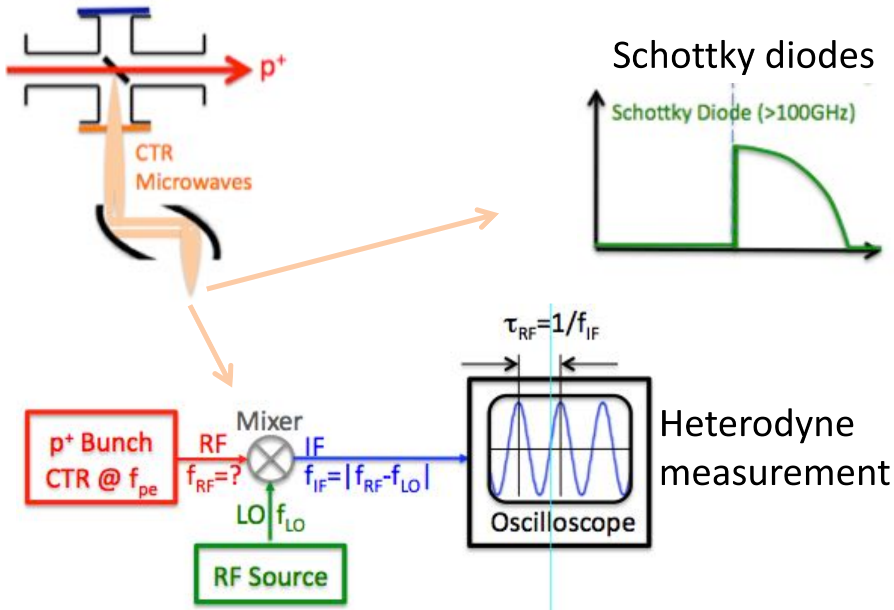
Direct SSM diagnostic: Measure frequency of modulation.

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

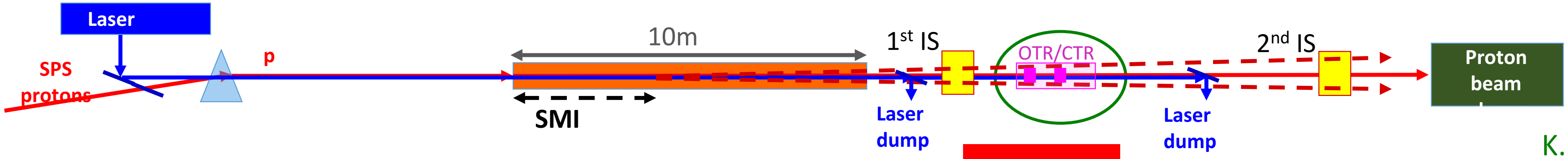


Streak Camera

CTR: Coherent Transition Radiation: Radiation is coherent for wavelengths bigger than the structure of the micro-bunches (90-300GHz).



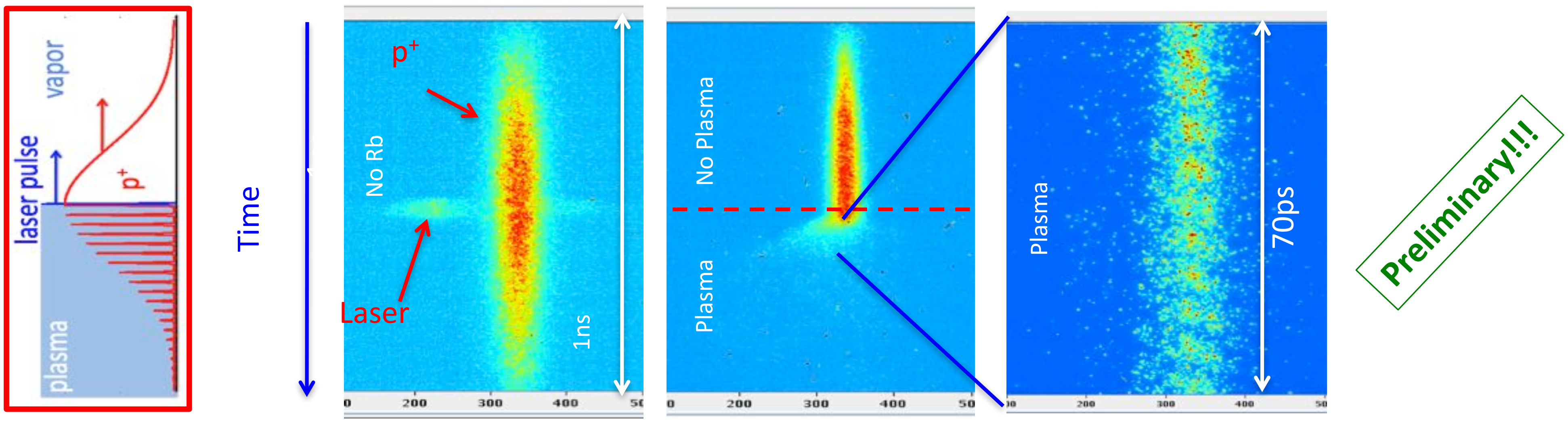
Direct Seeded Self-Modulation Results



K. Rieger, MPP

Streak camera Images

OTR

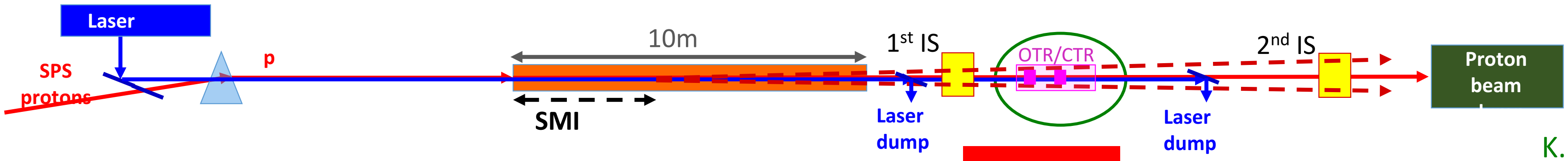


n_{Rb}=3.7x10^{14}cm^{-3}
→ $\lambda_{Rb\text{-}plasma}$ = 1.8 mm
→ f_{mod}~164 GHz

$N_{protons}$=3x10^{11}

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

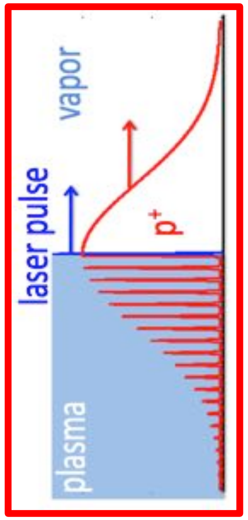
Direct Seeded Self-Modulation Results

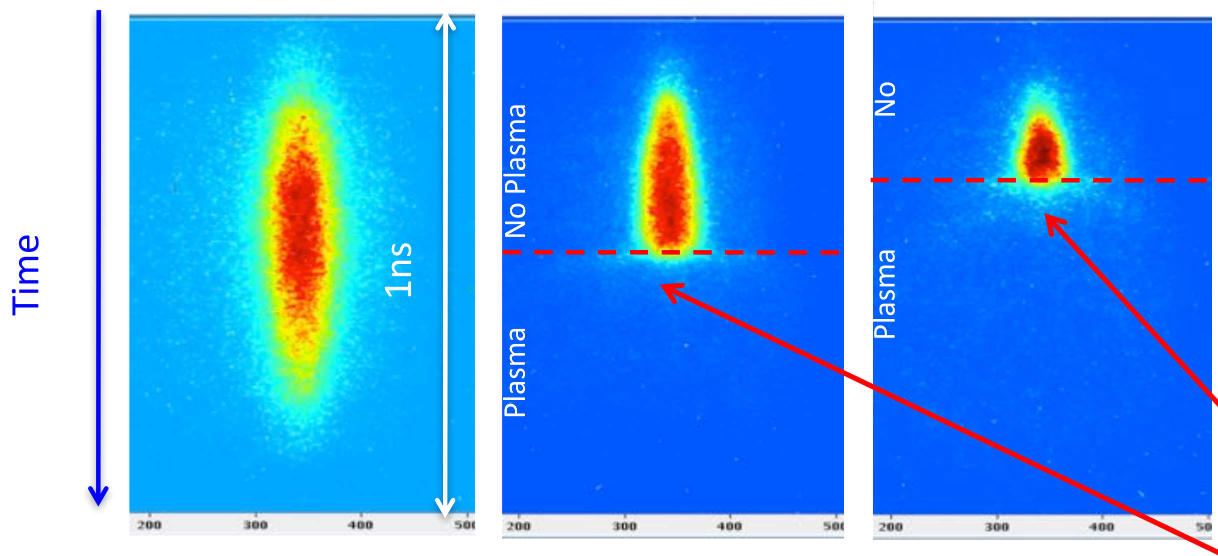


K. Rieger, MPP

Streak camera Images

OTR





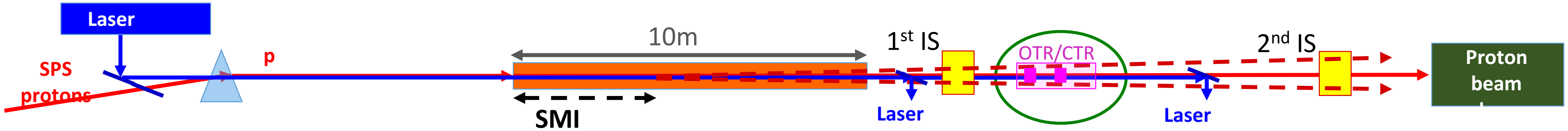
Preliminary!!!

$n_{Rb}=2.2\times10^{14}cm^{-3}$
$N=3\times10^{11}p^+$

- → Various seeding position/times
- → Effect starts at laser timing → SM seeding
- → Stronger effects with seed at ¼ than ½

p^+ symmetrically defocused by SSM

Direct Seeded Self-Modulation Results



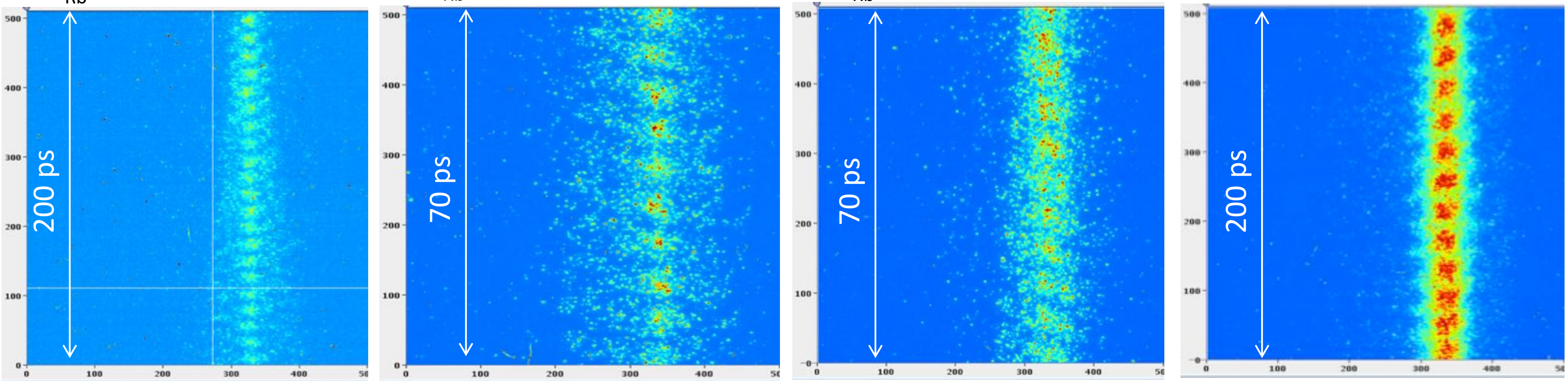
K. Rieger, MPP

Streak camera Images

Preliminary!!!

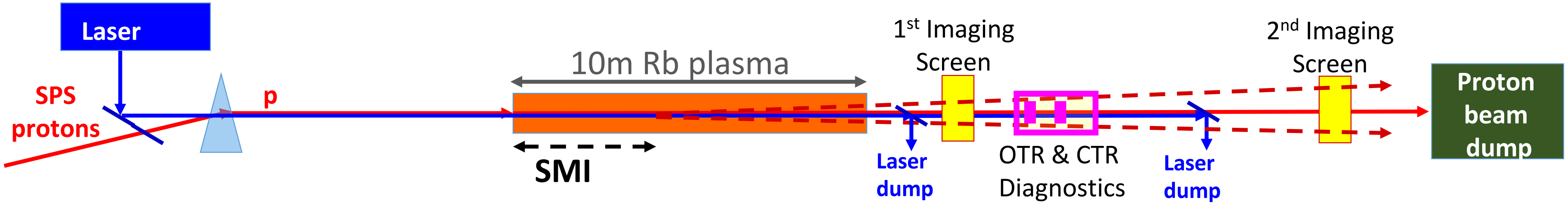
Micro bunches for different plasma densities

$n_{Rb}=1.3\times10^{14}cm^{-3}$ $n_{Rb}=2.0\times10^{14}cm^{-3}$ $n_{Rb}=2.6\times10^{14}cm^{-3}$ $n_{Rb}\sim 0.4\times10^{14}cm^{-3}$

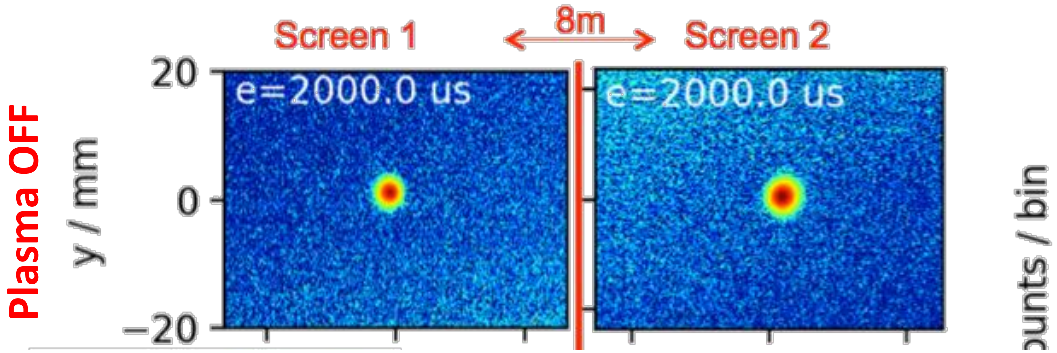


→ Observation of strong, persistent micro bunches for a range of plasma densities
→ Seeding is critical ingredient for producing many periods of micro bunches along the beam

Seeded Self-Modulation Diagnostics II



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

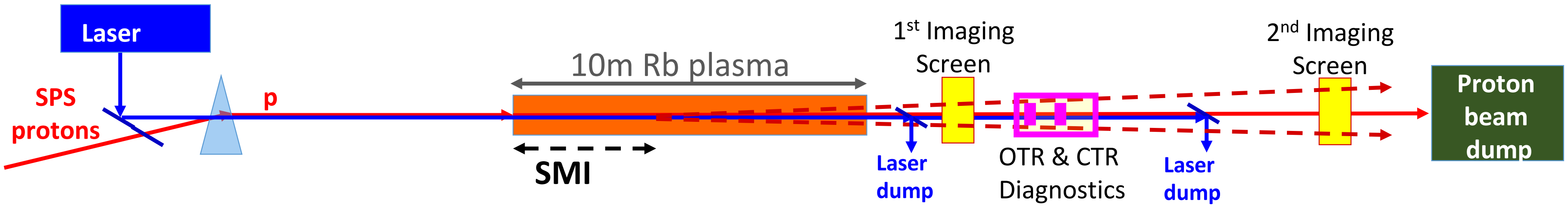


M. Turner, CERN

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.

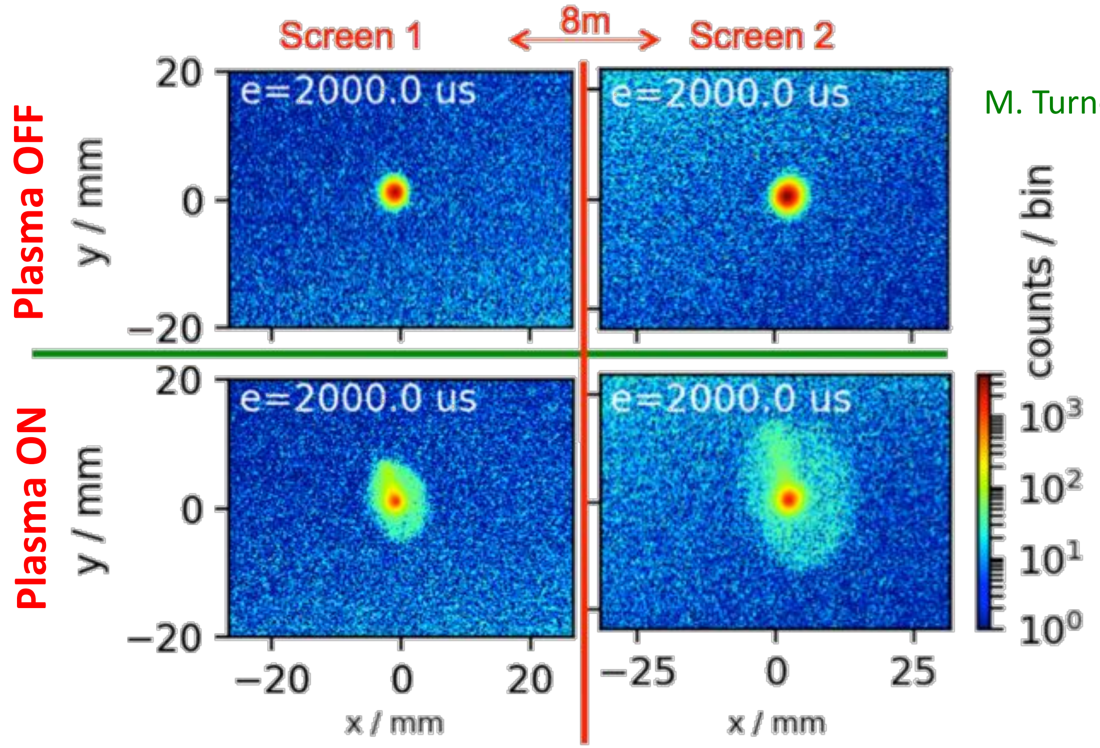
Indirect Seeded Self-Modulation Results



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 ($\int W_{per} dr$)

Preliminary!!!

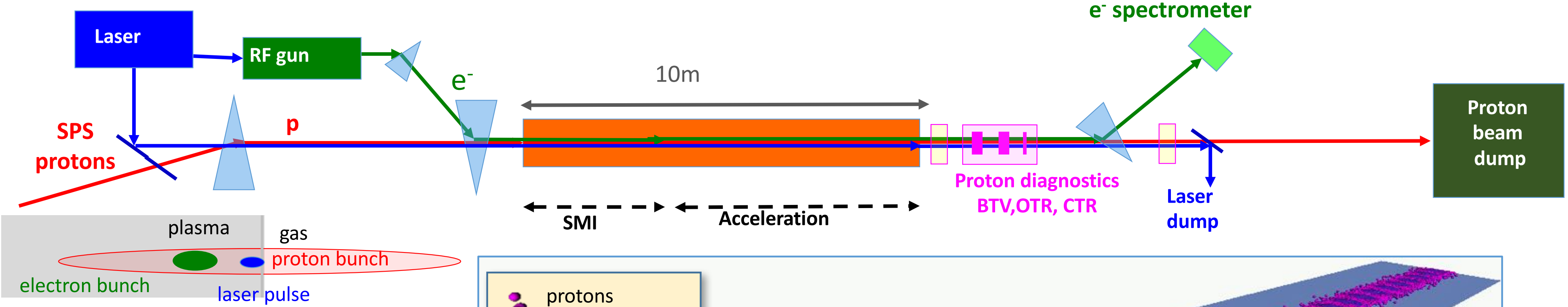


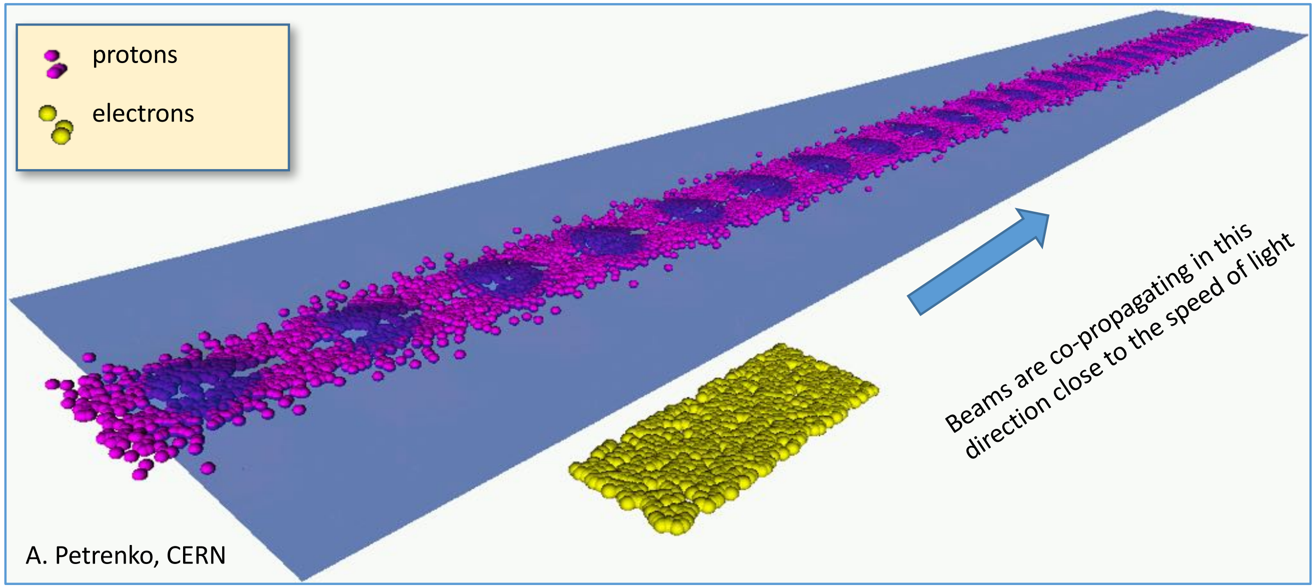
M. Turner, CERN

AWAKE Experiment: Electron Acceleration 2017/18

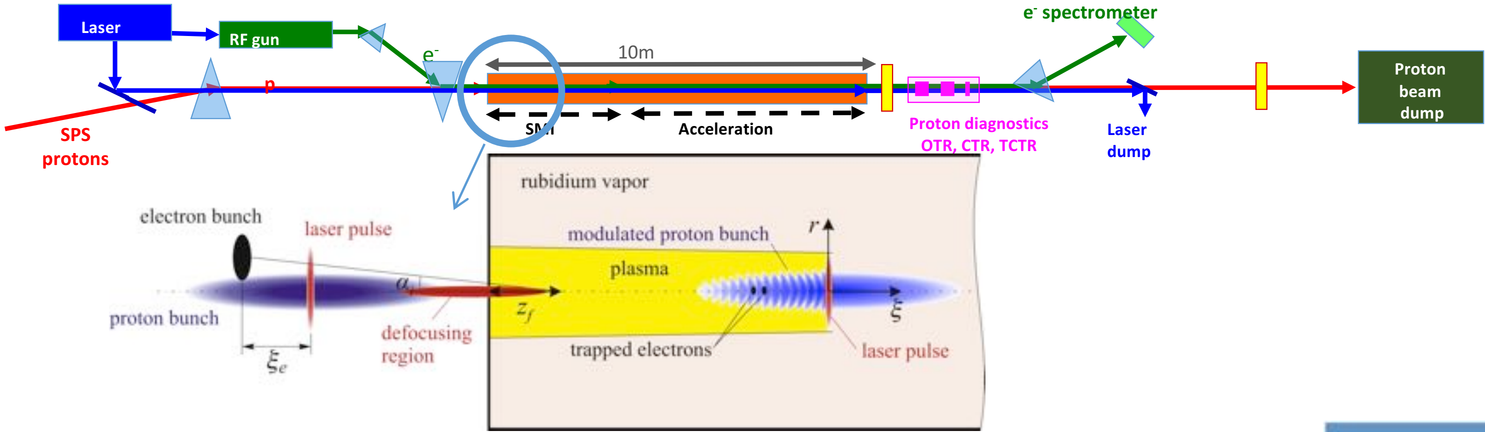
Phase 1: 2016/17: Understand **the physics of the seeded self-modulation** processes in plasma.

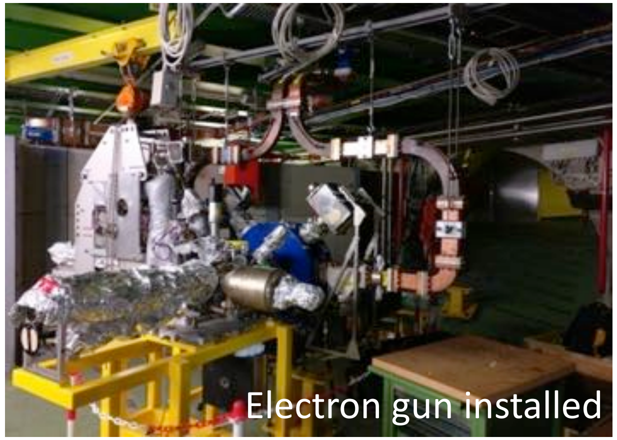
Phase 2: 2017/18: **Probe the accelerating wakefields** with externally injected electrons.

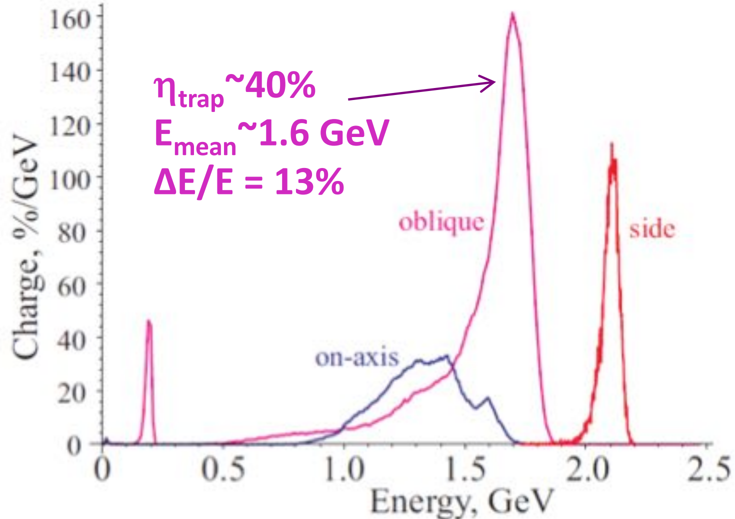




Electron Acceleration







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

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	Δp/p = 0.5%

Externally inject electrons and accelerate e^- to GeV energy with ~GeV/m gradient and finite ΔE/E
→ Start end 2017

Outline

- Motivation
- Plasma Wakefield Acceleration
- AWAKE
- Outlook

AWAKE Run 2

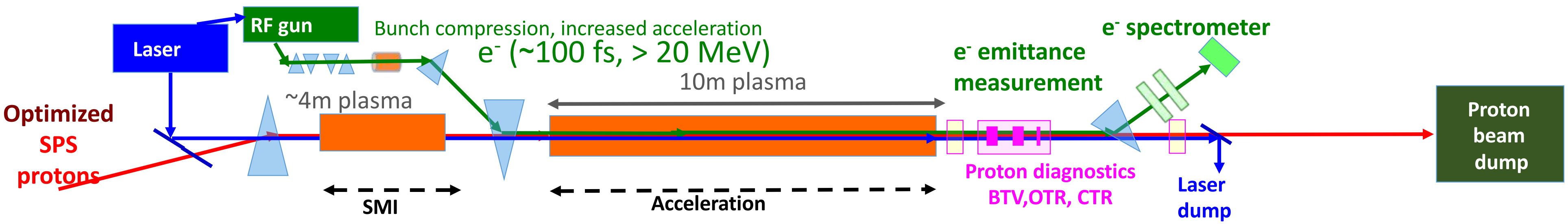
Proposing Run 2 for 2021 after CERN Long Shutdown 2

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)

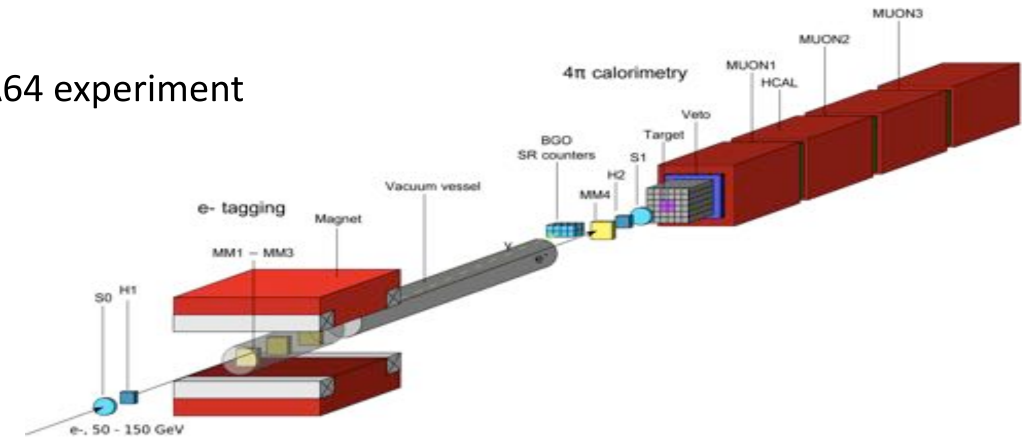
Application of Proton Driven Wakefield Acceleration Technology

- Use of electron beam for test-beam infrastructure, either/or for detector characterization and as an accelerator test facility.

- **Fixed target experiments** using electron beams, e.g. deep inelastic scattering.
  - Measure events at high parton momentum fraction, have polarized particles and look at spin structure; consider different targets.

- Search for dark photons a la NA64.
  - **AWAKE-like** electron beam driven by SPS proton bunch. Assuming 10^9 electrons/bunch, would give **3 orders of magnitude** increase compared to NA64 today.

NA64 experiment

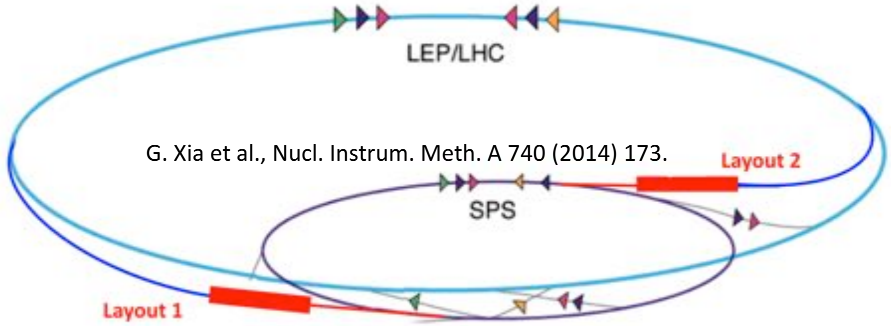


Application of Proton Driven Wakefield Acceleration Technology: Electron-Proton or Electron-Ion Collider

LHeC-Like:

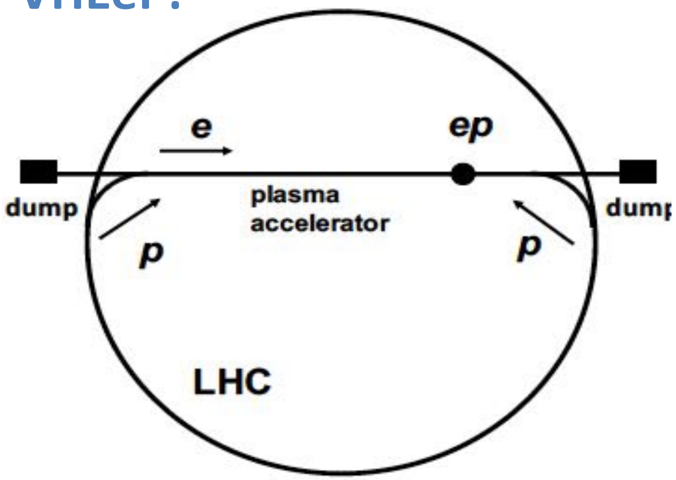
- **Focus on QCD:** Large cross sections → low luminosity enough (HERA level)
- Many open physics questions !

→ High energy ep collider: E_e up to O(50 GeV), colliding with LHC proton;
→ e.g. E_e = 10 GeV, Ep = 7 TeV, √s = 530 GeV already exceeds HERA cm energy.



Create ~50 GeV electron beam within 50−100 m of plasma driven by SPS protons, But luminosity < 10^{30} cm^{-2} s^{-1}.

VHEeP:



- Choose $\mathbf{E_e}$ **= 3 TeV** as a baseline and **with** $\mathbf{E_P}$ **= 7 TeV** yields √s = 9 TeV. Can vary.
- Centre-of-mass energy ~30 higher than HERA.
- Reach in (high) Q^2 and (low) Bjorken x extended by ~1000 compared to HERA.
- Opens new physics perspectives
- Luminosity ~ 10^{28} – 10^{29} cm^{-2} s^{-1} gives ~ 1 pb−1 per year.

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

Summary

- Plasma wakefield acceleration is an exciting and growing field with a huge potential.
- Many encouraging results in plasma wakefield acceleration technology.
- AWAKE is the first proton driven plasma wakefield acceleration experiment
  - Successfully observed the seeded Self-Modulation of the proton bunch in AWAKE.
  - Acceleration of electrons in the plasma wakefield driven by proton beam in 2018.
  - Short term prospects: demonstration of stable acceleration and good electron bunch properties.
  - Long term prospects: develop particle physics program that could be pursued with an AWAKE-like beam.