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

AWAKE

Plasma Wake Field Acceleration and the AWAKE Experiment

J. Moody

P. Muggli, A. Caldwell

Max Planck Institute for Physics

for the AWAKE Collaboration

B-Physics Workshop, Neckarzimmern,

22 March 2019

Outline of Lecture

Section I: Motivation for Charged Particle Accelerators

Section II: Acceleration of Particles

Section III: Plasma Wakefield Acceleration

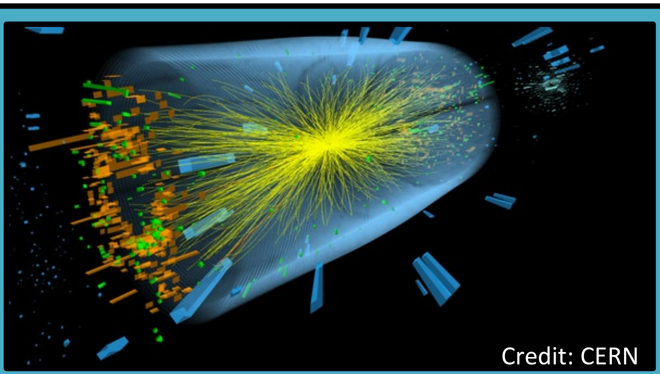
Section IV: The AWAKE Experiment

Section I

Motivation for Accelerators

What is the demand for charged particle accelerators for scientific research?

Colliders for High Energy Physics

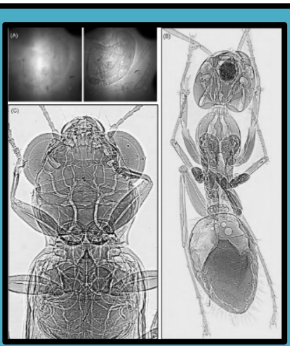

Credit: CERN

Collision at LHC

Many Others, for example:

Light Sources

Mass Spectroscopy



Phase Contrast X-ray image

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

High Energy Physics Colliders

AWAKE

Performance Considerations of Colliders for HEP

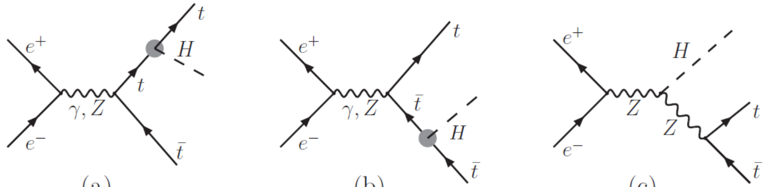
Center Momentum Energy:
Value and Spread

$$E_{\mathrm{cm}}^2 = (m_1^2 + m_2^2 + 2m_2E_{1,\mathrm{lab}})$$

Luminosity

$$\frac{dR}{dt} = L \cdot \sigma$$

Maximize Coupling
And
Minimize Background



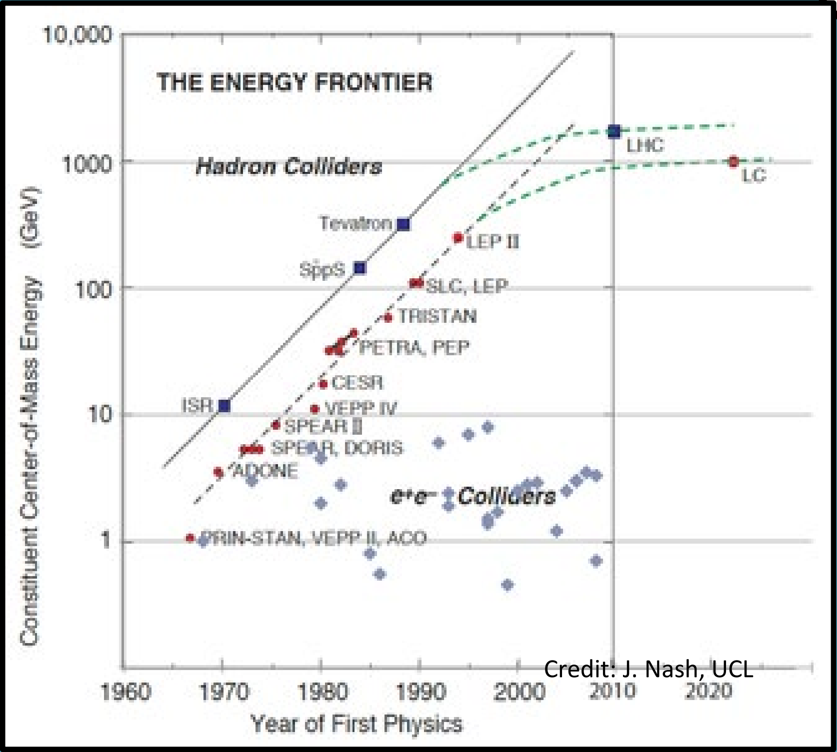
(a) (b) (c)

MAX-PLANCK-GESELLSCHAFT

To Higher CM Energy Scales

Challenges for Higher CM Energy

- Scale of Linear Accelerators
- Synchrotron radiation for circular electron machines
- Scale / maximum magnetic field for circular hadron accelerators
- Resource use scales with collider size, next generation colliders in Billions of USD



Credit: J. Nash, UCL

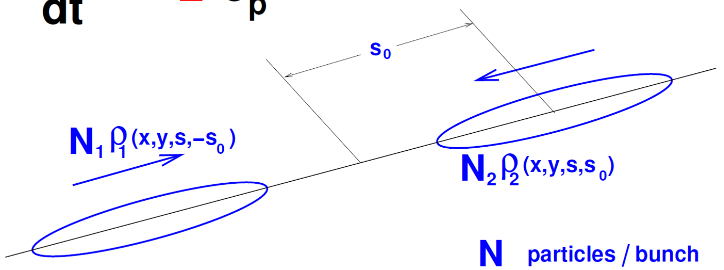
Livingston Plot

How to achieve physics goals with limited resources? Decrease size, Increase Gradients!

Luminosity

Luminosity for Particle Collider

$$\frac{dR}{dt} = L\,\sigma_p$$



N particles / bunch

ρ density ≠ const.

$$\boxed{\frac{dR}{dt}} = \boxed{L} \cdot \boxed{\sigma}$$

Rate

Luminosity

Energy dependent Crosssection

$$\mathcal{L} \propto \boxed{K} \cdot \iiint_{-\infty}^{+\infty} \boxed{\rho_1(x,y,s,-s_0)}\,\boxed{\rho_2(x,y,s,s_0)}\,dx\,dy\,ds\,ds_0$$

Maximize particle densities over interaction length
What does this mean? Small spot size, high brightness, high rep rate

Werr, Murartori “Concept of Luminosity“

Section II
Acceleration of Particles

The Lorentz Force

$$\mathbf{F} = \frac{dp}{dt} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

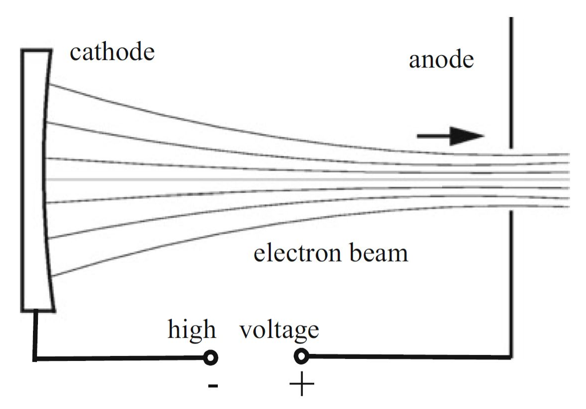
$$\Delta E_{Kinetic} = \int q(\boldsymbol{E} \cdot \boldsymbol{v})\, ds$$

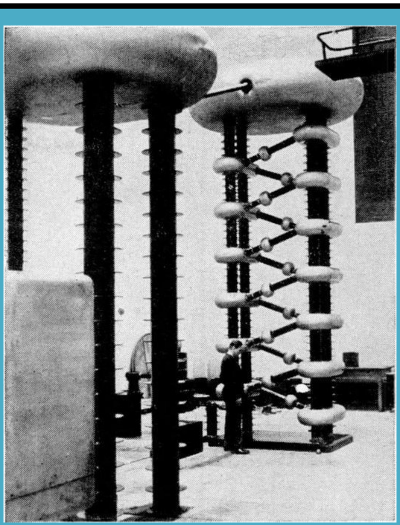
If E is a wave then it can dephase and even decelerate

How to generate Electric Field to accelerate particles?

Electrostatic Accelerators

- Electric field accelerates charged particles
- Relatively low accelerating gradients (MeV scale energy gain on large devices)
- Suffer from **breakdown**
- Breakdown limits the accelerating gradients!





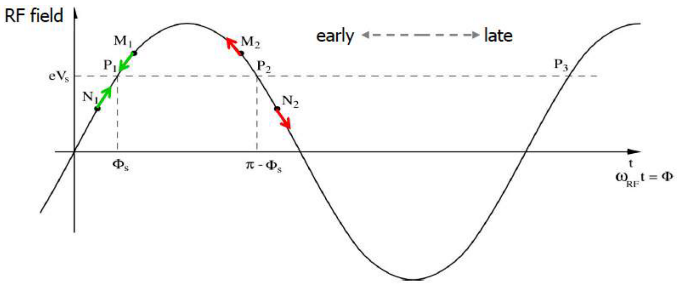
Cockcroft-Walton
Electrostatic Accelerator

How to overcome breakdown?

Let the field frequency, $\omega \neq 0$

H. Wiedemann, Particle Accelerator Physics

Acceleration by RF Fields



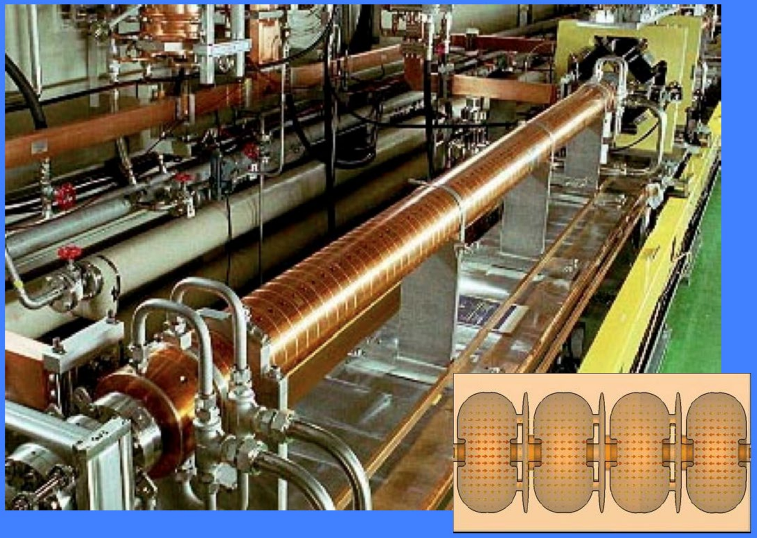
Typical SLAC Cavity style Parameters:

Frequency: S-band (~3 GHz)

Gradient: ~20MeV/m

Cavity Length: 1.5 m

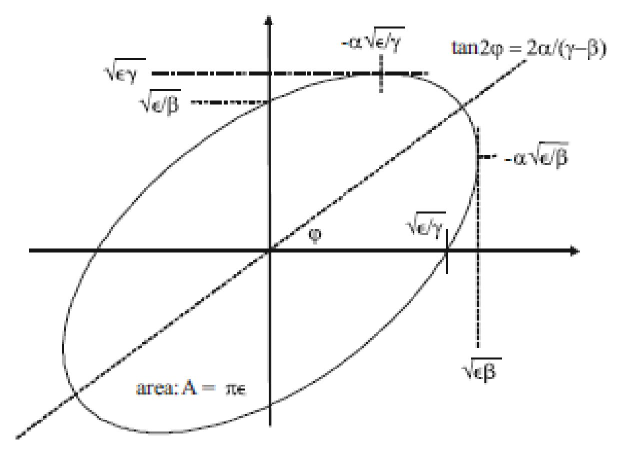
Conventional RF accelerating structures



Beam Distributions

How do we describe beams?

- Liouville’s Theorem allows us to describe a beam’s evolution as an area occupied in phase space instead of individual particle trajectories
- Emittance is a measure of this phase space area occupied by the beam
- We typically assume rotational symmetry and can describe them by longitudinal and transverse phase spaces



More on Transverse Emittance

Geometric Emittance (RMS)

RMS emittance definition:

$$\varepsilon_{geo\,x} = [\pi]\left(\langle x^2\rangle\langle x'^2\rangle - \underbrace{\langle xx'\rangle}_{\text{Correlation term}}{}^2\right)^{1/2} \qquad \langle\ldots\rangle \text{ average } \Rightarrow \langle x^2\rangle^{1/2} \text{ RMS size}$$

$$\Rightarrow \langle x'^2\rangle^{1/2} \text{ ~RMS transverse velocity or temperature}$$

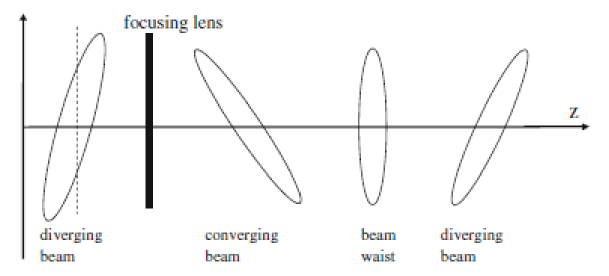
$$\varepsilon_{geo\,x} = \left(\langle x^2\rangle\langle x'^2\rangle\right)^{1/2} \cong \sigma_x \frac{\sigma_{p_x}}{\beta\gamma mc} \propto \frac{1}{\gamma}$$

Geometric emittance decreases upon acceleration

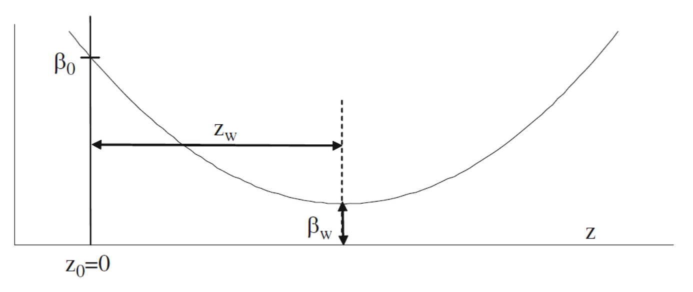
Why Do We Care About Emittance?

Emittance effects Luminosity!

The waist size at the interaction final focus is determined by the emittance
This determines the particle density over the collision



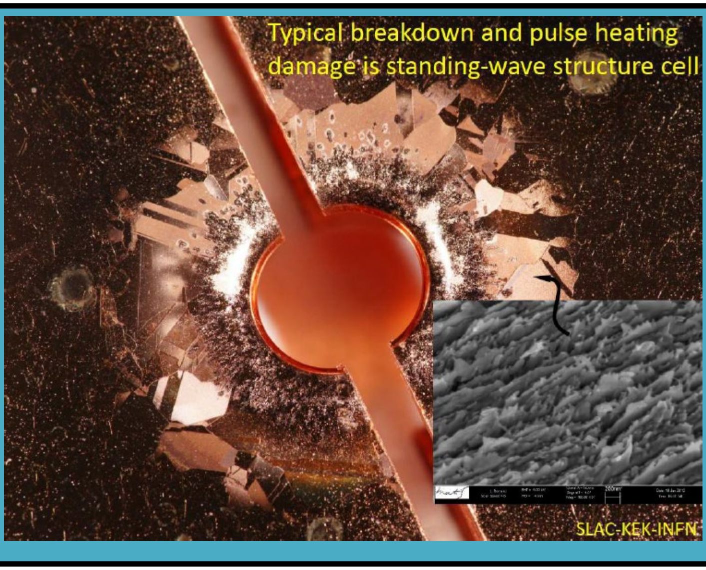
$$x_i(z) = \sqrt{\epsilon}\sqrt{\beta(z)}\cos[\psi(z) + \delta_i]$$



Limitations to Conventional RF Accelerators

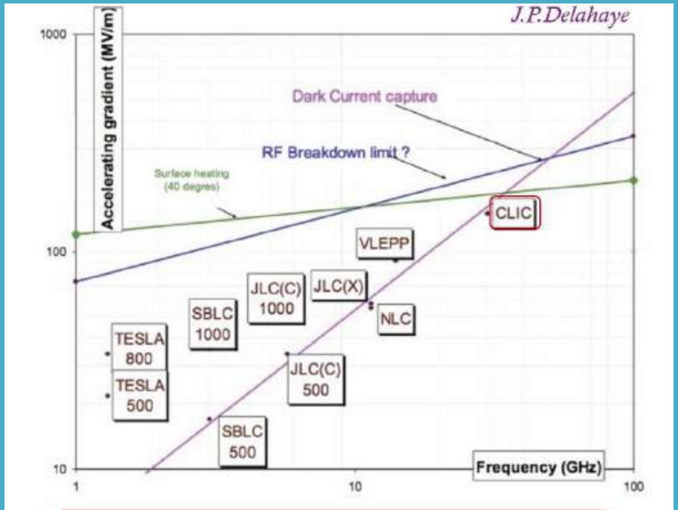
Breakdown for traditional S-band type RF accelerators limits accelerating gradients to around ~200 MeV/m

Practical limitation: once breakdown occurs structures are degraded



Typical breakdown and pulse heating damage is standing-wave structure cell

SLAC-KEK-INFN

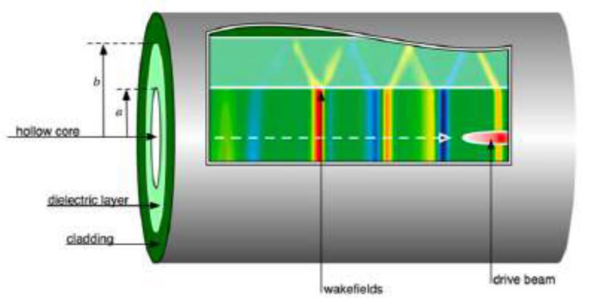


Breakdown limits metal:

$$E_s = 220(f[\mathrm{GHz}])^{1/3}\ \mathrm{MV/m}$$

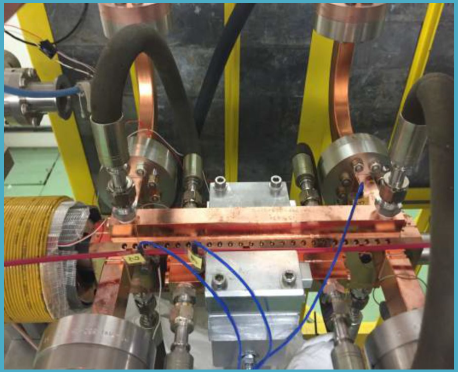
Advanced Accelerators

How do we go to shorter wavelengths for our accelerating fields?

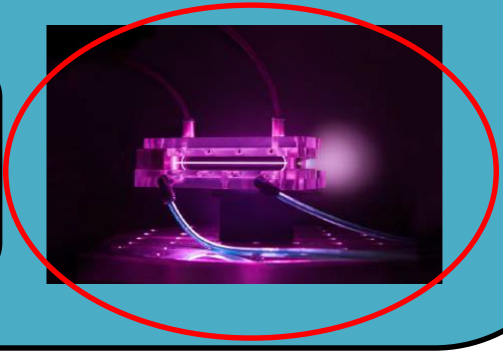


Dielectric Wakefield

Higher Frequency RF



Plasma



Because we are operating at shorter than conventional wavelengths all advanced accelerators have a challenge for **Beam quality: Energy spread and transverse emittance**

Section III
Plasma Wakefield Acceleration

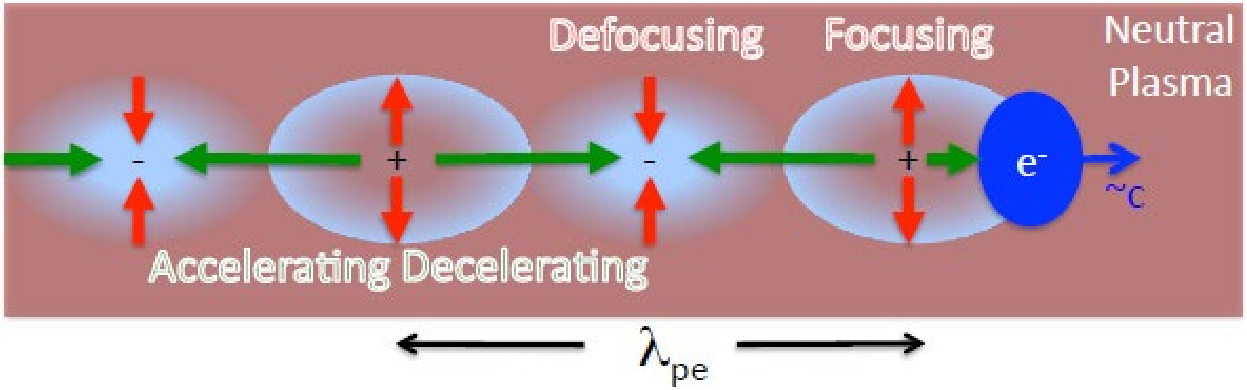
- Often a boat wake is used as an analogy of plasma wakefields
- A boat travels faster than the oscillations in the medium
- Leaves behind energy in the medium
- Can extract the energy left behind, like a wake surfer

Plasmas

Neutral
Plasma

- Plasmas are more than just ionized gases
- Typically need a large number of particles within a plasma length scale
- They exhibit collective effects example: Debye screening
- The are quasi neutral $n_{e0}=n_{i0}$
- For our purposes we shall assume the ions fixed (M_i >> M_e)
- Exhibit a response on a characteristic timescale of $\omega_{pe}=(n_e e^2/\varepsilon_0 m_e)^{1/2}$

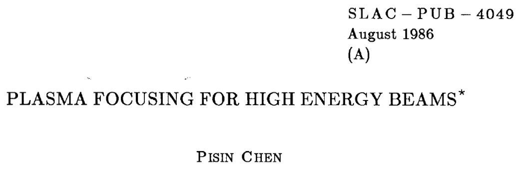
Plasma Wakefield Concept



- Space charge force from drive beam pushes plasma electrons
- Plasma electrons are perturbed and oscillate at
- If in the linear regime only a quarter period of wak $\omega_{pe}=(n_e e^2/\varepsilon_0 m_e)^{1/2}$ focusing and accelerating simultaneously
- Can create fields that are phase locked to the driver
- Max strength of the fields the cold plasma wave breaking field: $E_z \approx E_{WB} = m_e c \omega_{pe} / e$
- For PWFA : $E_z \approx \frac{n_b}{n_{e0}} E_{BW}$

Wakefield Equations
Linear Theory

Good Background from Chen



SLAC – PUB – 4049
August 1986
(A)

PLASMA FOCUSING FOR HIGH ENERGY BEAMS*

PISIN CHEN

Assume coordinate frame comoving with driver: $\varsigma \equiv z - ct$

Apply assumption of nonrelativistic cold fluid limit

Linearize equations (expand to first order)

$$-\partial_\varsigma \vec{v}_1 = -\frac{e}{mc}\vec{E}_1$$ Fluid Momentum

$$-c\partial_\varsigma n_1 + n_0 \nabla \cdot \vec{v}_1 = 0$$ Fluid Continuity

$$\partial_\zeta^2 n_1 + k_p^2 n_1 = \mp k_p^2 \sigma(\vec{x})$$

Linear Wakefield Theory

Longitudinal Wakefield

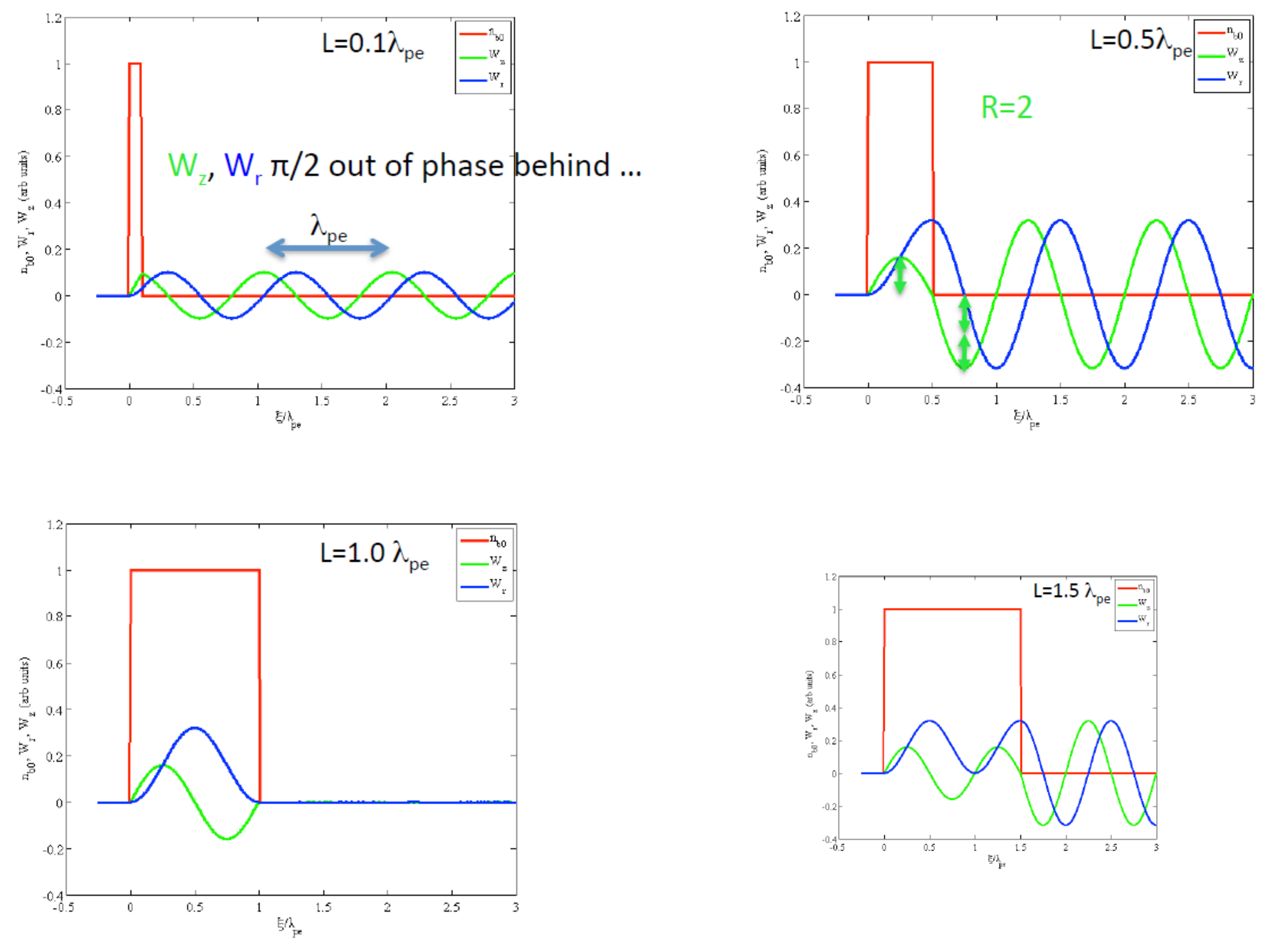
$$W_z(\xi,r) = \frac{en_{b0}}{\epsilon_0}\int_{-\infty}^{\xi} n_{b_\parallel}(\xi')cos[k_{pe}(\xi-\xi')]d\xi' \cdot R(r), \qquad W_z = eE_z$$

$$W_\perp(\xi,r) = \frac{en_{b0}}{\epsilon_0 k_{pe}}\int_{-\infty}^{\xi} n_{b_\parallel}(\xi')sin[k_{pe}(\xi-\xi')]d\xi' \cdot \frac{dR(r)}{dr}, \qquad W_r = e\left(E_r - v_b \times B_\theta\right)$$

Transverse Wakefield

with $n_b = n_{b0}f(r,\xi) = n_{b0}n_{b_\parallel}(\xi)n_{b\perp}(r)$

Test Case:
Step Function Drive Bunches



L=0.1λ_{pe}

W_z, W_r π/2 out of phase behind …

λ_{pe}

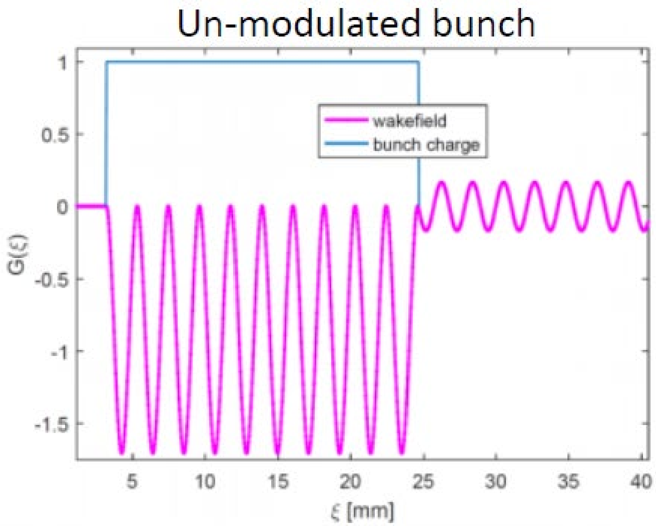
L=0.5λ_{pe}

R=2

L=1.0 λ_{pe}

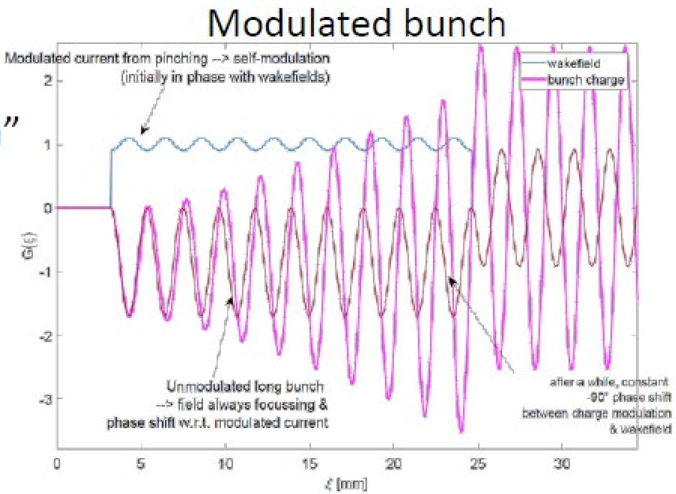
L=1.5 λ_{pe}

Test Case:
Longer Drive Bunches


Un-modulated bunch

"Propagation"

"Evolution"


Modulated bunch

Calculation: F. Braunmueller

- ✧Modulated bunch drives larger wakefields than un-modulated bunch
- ✧Wakefields shift backwards from the front of the bunch
- ✧Growth of the wakefields, transverse evolution of the bunch …

Transformer Ratio

Transformer Ratio

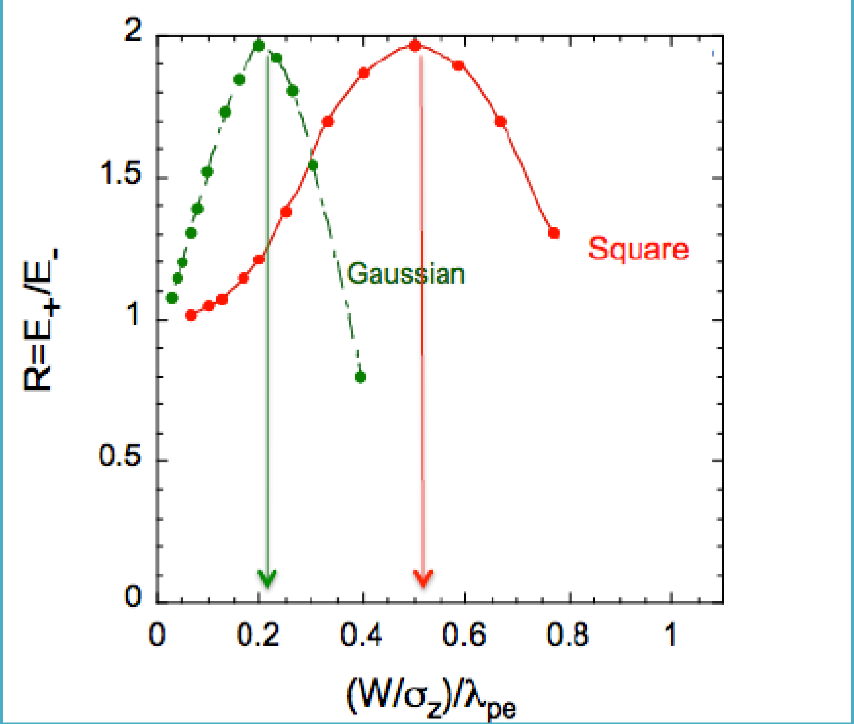
Optimum Depends on bunch shape

For Gaussian maximum R is at
$k_{pe}\sigma_z \sim \sqrt{2}$

For a square bunch
It is $\lambda_{pe}/2$

The transformer ratio is a reflection of how much energy can be transferred from the drive to the witness beam

$R=|W_{z,max}(\text{behind})|/|W_{z,max}(\text{within})|$



Transformer Ratio R>2

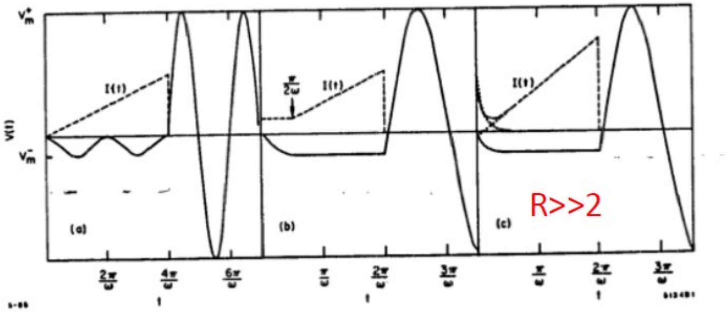
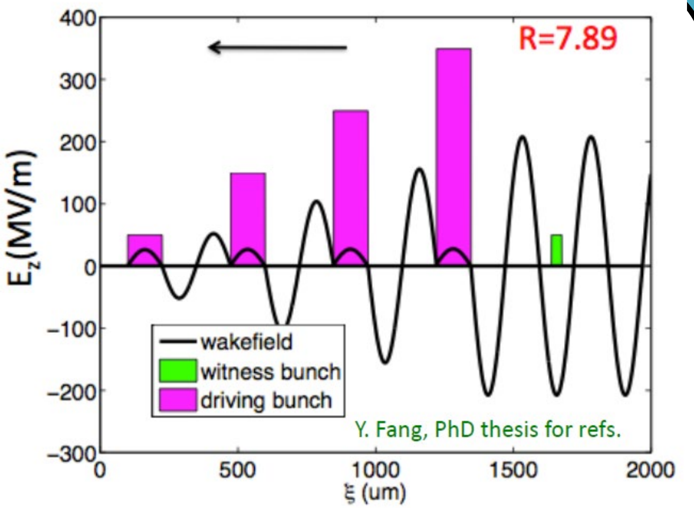


Figure 9. The voltage induced by three different asymmetric current distributions interacting with a single mode.

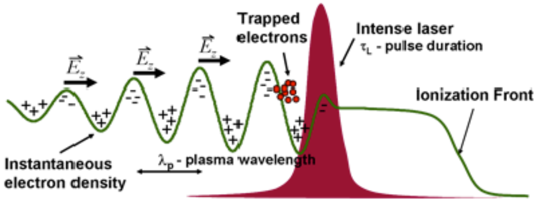


Y. Fang, PhD thesis for refs.

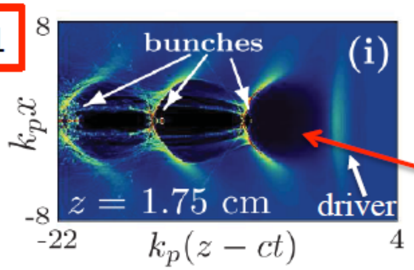
- R=2 is for a length optimized gaussian bunch but can we go higher?
- We already saw that the transformer ratio is affected by bunch shape
- Ramping the drive beam current can drive stronger wakefields within the plasma

Blowout or Bubble Regime

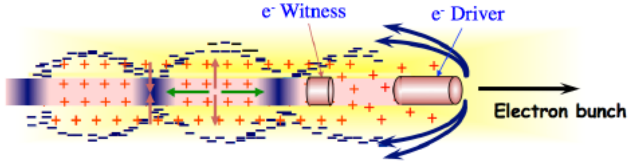
Laser WakeField Accelerator

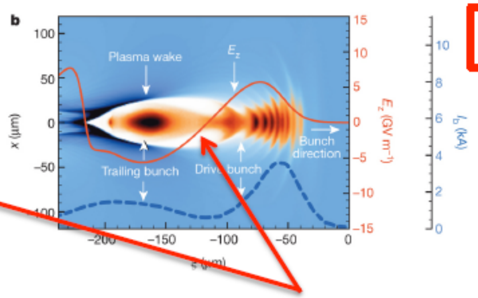


a_0>>1



Plasma WakeField Accelerator





n_b/n_{e0}>>1

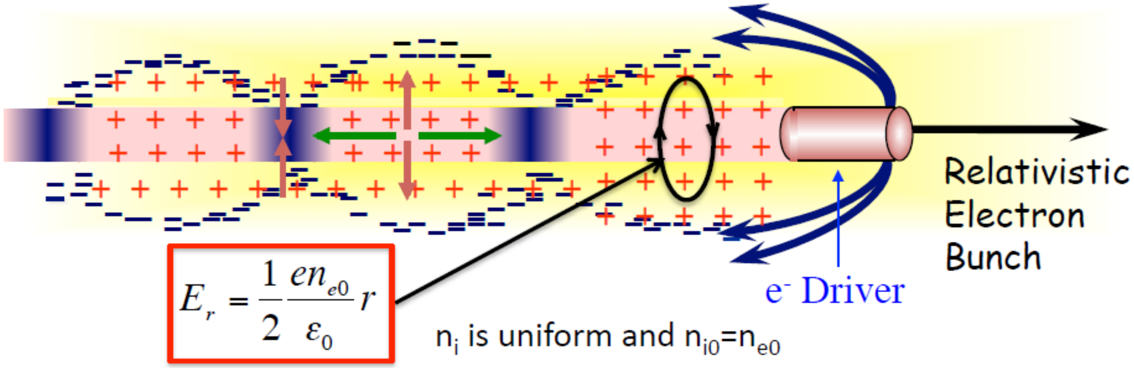
No more plasma electrons
Pure ion column

- ✧Regime most people are most familiar with …
- ✧Most useful regime for e⁻ bunches acceleration …
- ✧E_z~E_{WB} ("linear concept")

LWFA: Pukhov, Appl. Phys. B., Lasers Opt. 74, 355 (2002)
PWFA: Rosenzweig, Phys. Rev. A 44, R6189 (1991)
Lu, PRL 96, 165002 (2006)

Bare Ion Column Focusing in Blowout

PURE (uniform) ION COLUMN FOCUSING



$$\boxed{E_r = \frac{1}{2}\frac{en_{e0}}{\varepsilon_0} r}$$

n_i is uniform and $n_{i0}=n_{e0}$

Motion of a particle in the ion column:

$$\gamma m_e \frac{dv_\perp}{dt} = F_\perp \quad \Rightarrow \quad \gamma m_e c^2 \frac{d^2r}{dz^2} = e\frac{1}{2}\frac{en_{e0}}{\varepsilon_0} r \quad \Rightarrow \quad \frac{d^2r}{dz^2} = \frac{1}{2\gamma c^2}\frac{e^2 n_{e0}}{m_e \varepsilon_0} r = \frac{\omega_{pe}^2}{2\gamma c^2} r = \frac{k_{pe}^2}{2\gamma} r = k_\beta^2 r$$

Harmonic motion (no energy gain/loss)

Dependent on γ!

$$\frac{d^2r}{dz^2} = k_\beta^2 r \quad \Rightarrow \quad r(z) = r_0 e^{ik_\beta z}$$

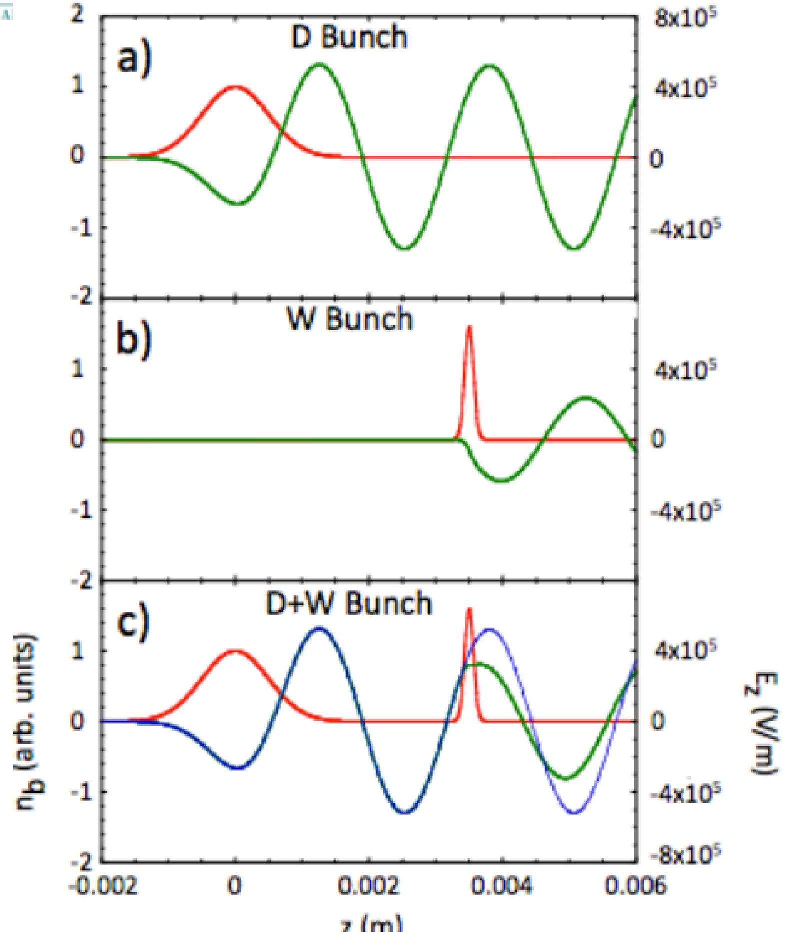
=> emission of betatron radiation (synchrotron)

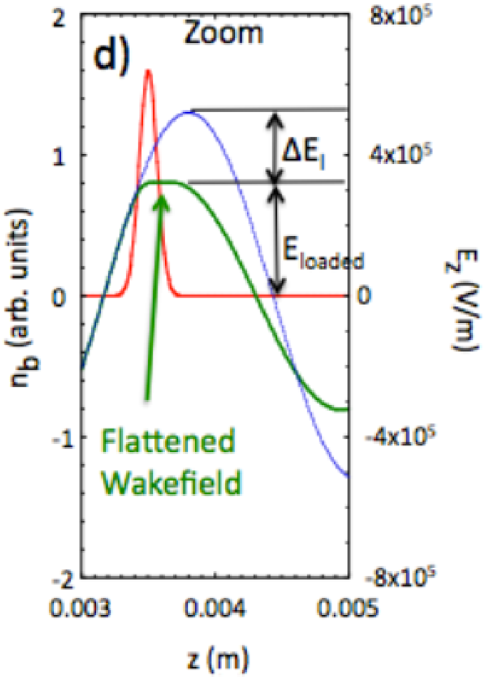
Examples: SLAC E_{kin}=28.56GeV => γ~56’000

n_e~2×10^{14}cm^{-3} => KeV photons Wang, PRL 88, 135004 (2002)

n_e~2×10^{17}cm^{-3} => MeV photons Johnson, PRL 97, 175003 (2006)

Beam Loading



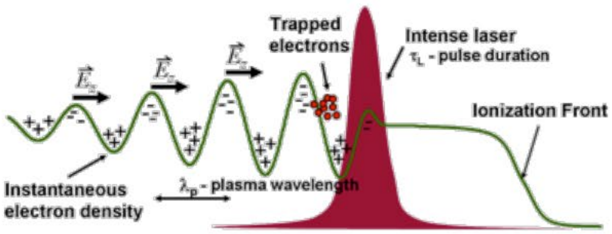


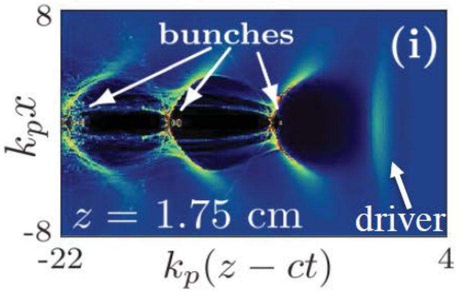
- ✧Leads to lower accelerating
- ✧Leads to lower R

This is required to lower the energy spread

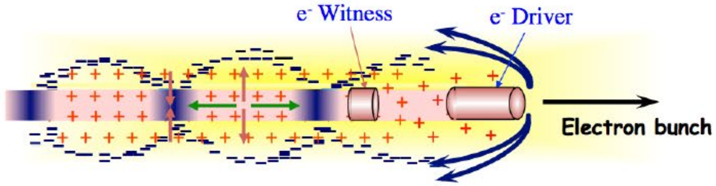
LWFA vs PWFA (beam driven)

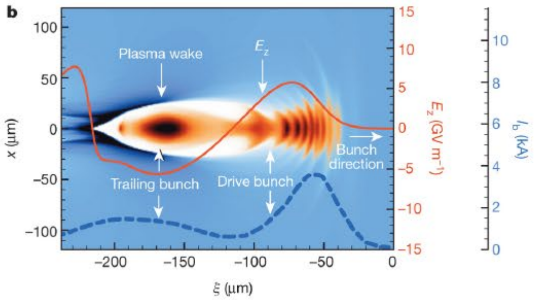
Laser WakeField Accelerator





Plasma WakeField Accelerator





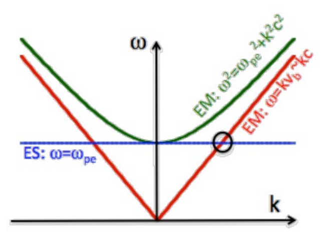
LWA

- Pondermotive force of laser drives plasma wakes
- Dephasing

$$v_g = \frac{\partial \omega}{\partial k} = \left(1 - \frac{\omega_{pe}^2}{\omega^2}\right)^{1/2}$$

This is can be significantly less than c and dependent

$$\omega^2 = \omega_{pe}^2 + k^2c^2$$



PWFA

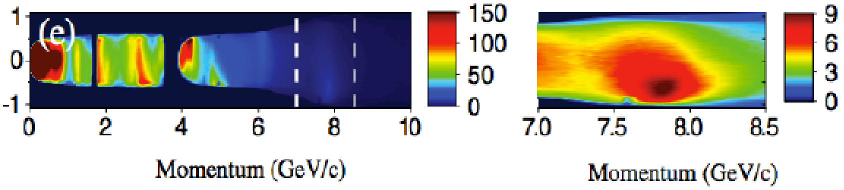
- Beam E-field drives wakefield
- Wakefield phase tied to driver velocity, close to c for very relativistic beams

$$v_p = \left(1 - \frac{1}{\gamma^2}\right)^{1/2} c \overset{\gamma^2 >> 1}{\cong} c$$

LWFA vs PWFA Results

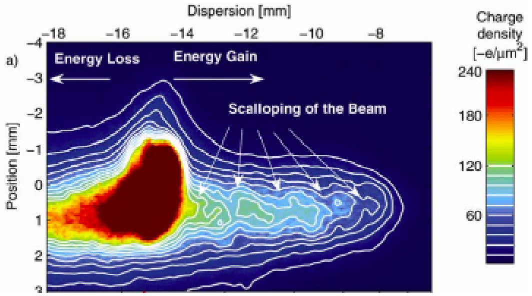
LWA: 20cm, ~8GeV

Gonsalves, Phys. Rev. Lett. 122, 084801, 2019



PWFA: 85cm, ~42GeV

Blumenfeld, Nature 445, 741 (2007)



Rayleigh length of laser beam

Beta function or particle beams (at waist)

$$Z_R = \pi \frac{w_0^2}{\lambda_0} \Leftrightarrow \beta^* = \beta_0 = \frac{\sigma_0^{*2}}{\varepsilon_g} \qquad \varepsilon_g = \frac{\varepsilon_N}{\gamma}$$

Laser pulse:

W_0=20µm

λ_0=800nm

Z_R=1.6mm

Z_R=64cm

λ_0=2nm

$$\boxed{\frac{\lambda_0}{\pi} \Leftrightarrow \varepsilon_g}$$

SLAC e$^-$ beam:

ε_N=50mm-mrad

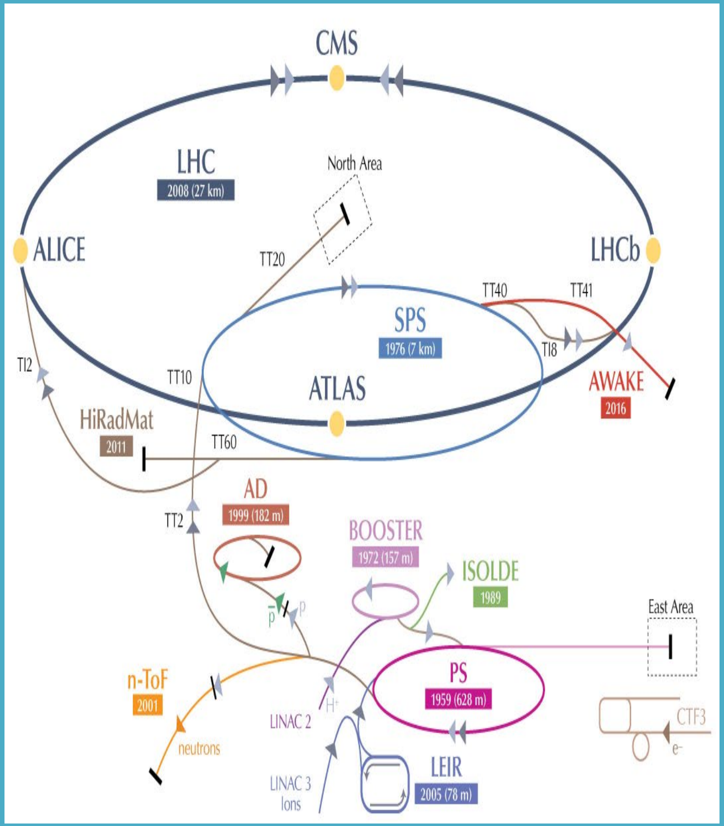
γ=80’000 (40GeV)

ε_g=6.25x10^{-10}m-rad

σ_0=20µm

β_0=64cm

Section IV
The AWAKE Experiment



Proton Driven Plasma Wakefield Acceleration Experiment

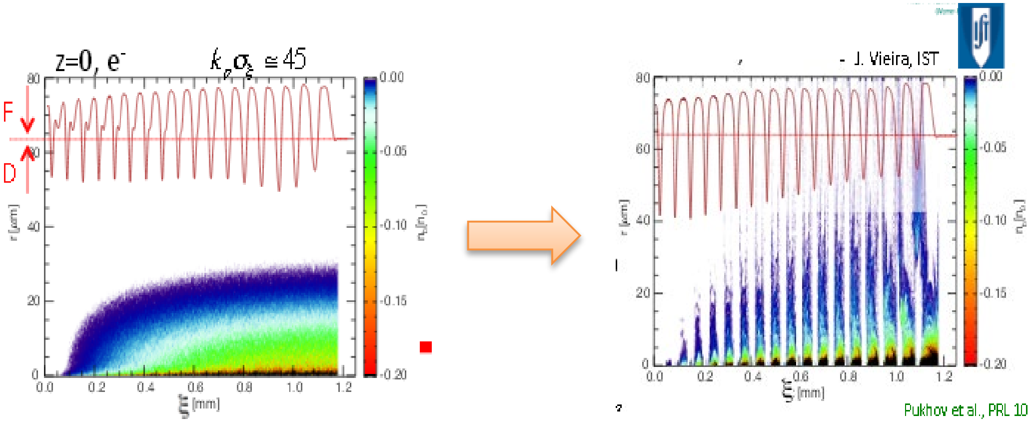
- Proof-of-Principle Accelerator R&D experiment at CERN
- 400 GeV protons from SPS drive wakefields through 10 m plasma
- Final Goal: Design high quality & high energy electron accelerator based on acquired knowledge.
- AWAKE Collaboration: 16 institutes + 3 associate
- Currently AWAKE is at a stage of a beam-plasma experiment

Driving with Protons

- 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 = 1.2mm)**

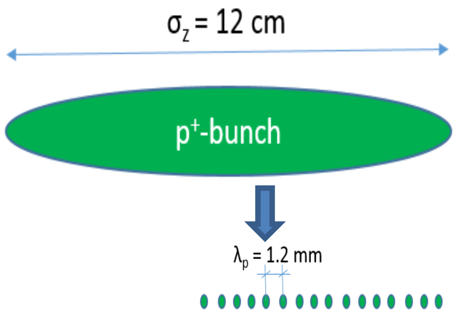
Seeded Self-Modulation

- 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 with period of λ_{pe} due to transverse wakefield in plasma
  - →**Resonantly drives the longitudinal wakefield**



N. Kumar, A. Pukhov, K. Lotov,
PRL 104, 255003 (2010)

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



Why Drive with Protons?

Proton bunches as drivers of plasma wakefields are interesting because of the very large energy content of the proton bunches.

Drive beams:

Lasers: ~40 J/pulse

Electron drive beam: 30 J/bunch

Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

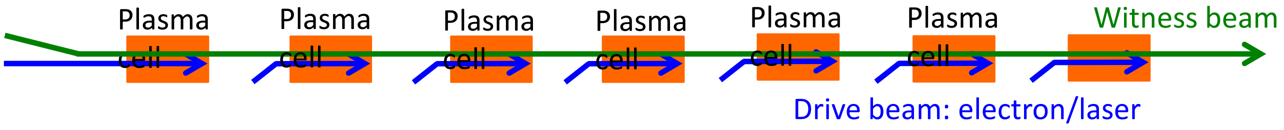
Witness beams:

Electrons: 10^{10} particles @ 1 TeV

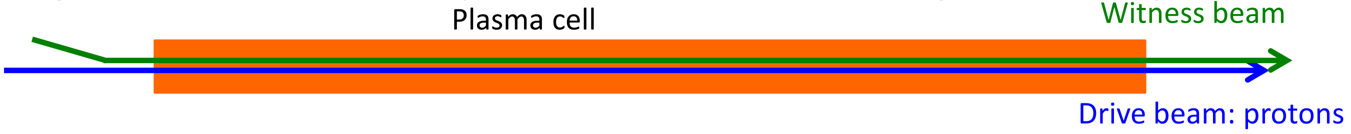
~few kJ

To reach TeV scale:

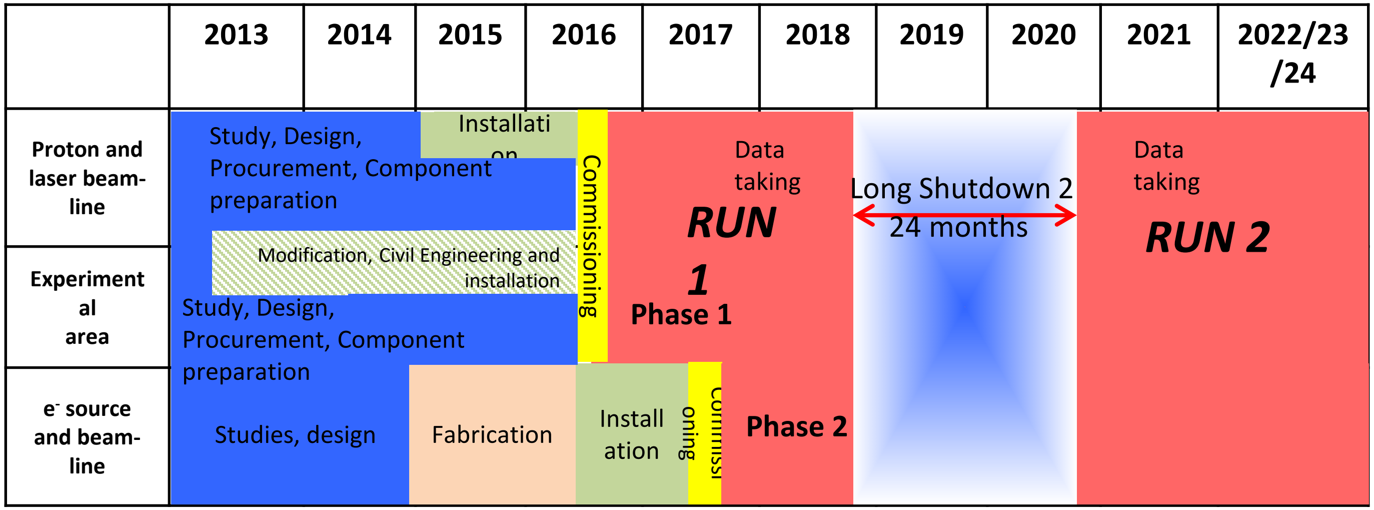
- Electron/laser driven PWA: need several stages, and challenging wrt to relative timing, tolerances, matching, etc…
  - effective gradient reduced because of long sections between accelerating elements….



- **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.



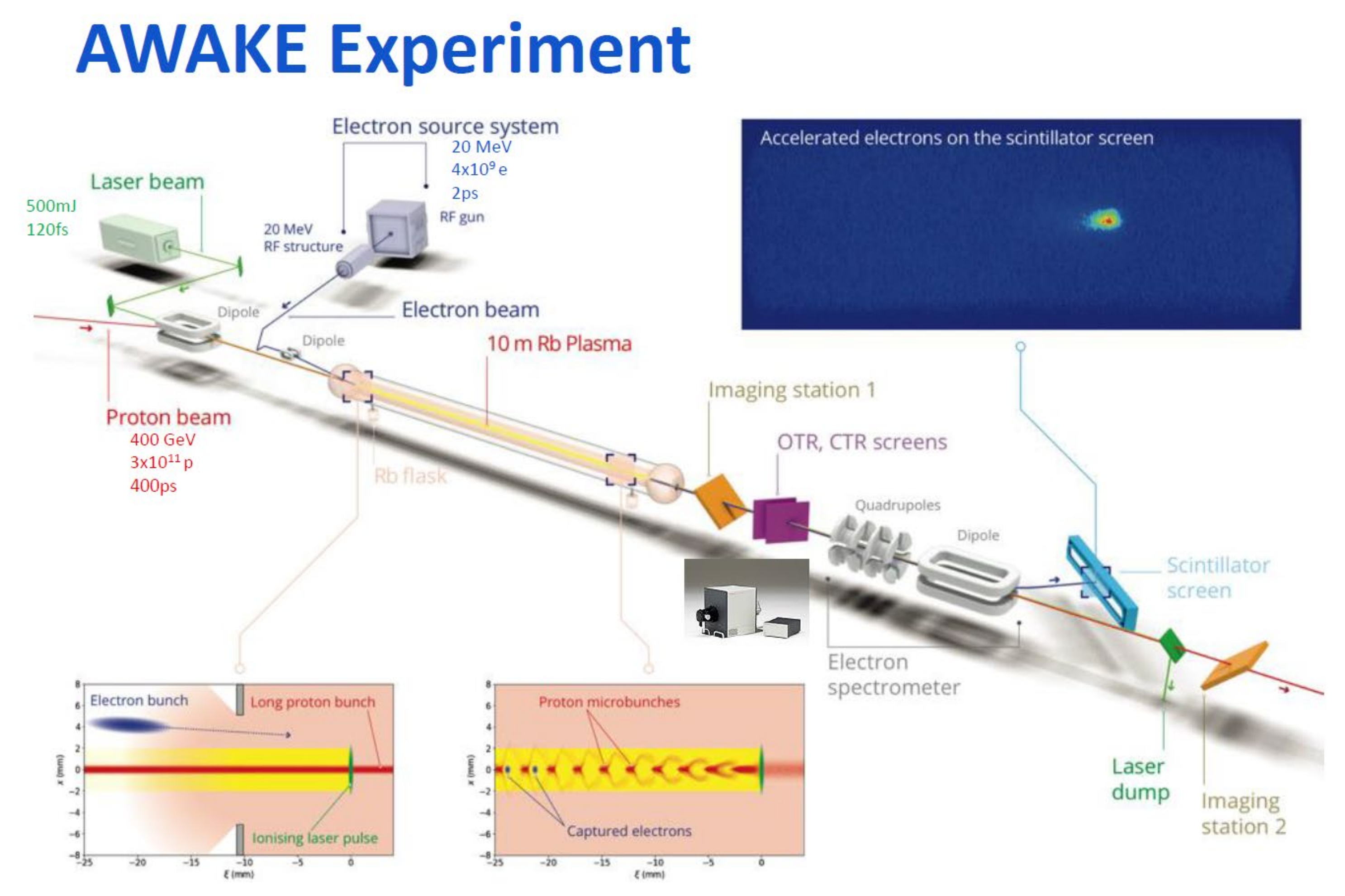
The AWAKE Experiment



	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022/23 /24
Proton and laser beam-line	Study, Design, Procurement, Component preparation		Installation	Commissioning	Data taking ***RUN 1***		Long Shutdown 2 ↔ 24 months		Data taking ***RUN 2***	
Experimental area	Modification, Civil Engineering and installation Study, Design, Procurement, Component preparation				**Phase 1**					
e⁻ source and beam-line	Studies, design		Fabrication	Installation	Commissioning	**Phase 2**				

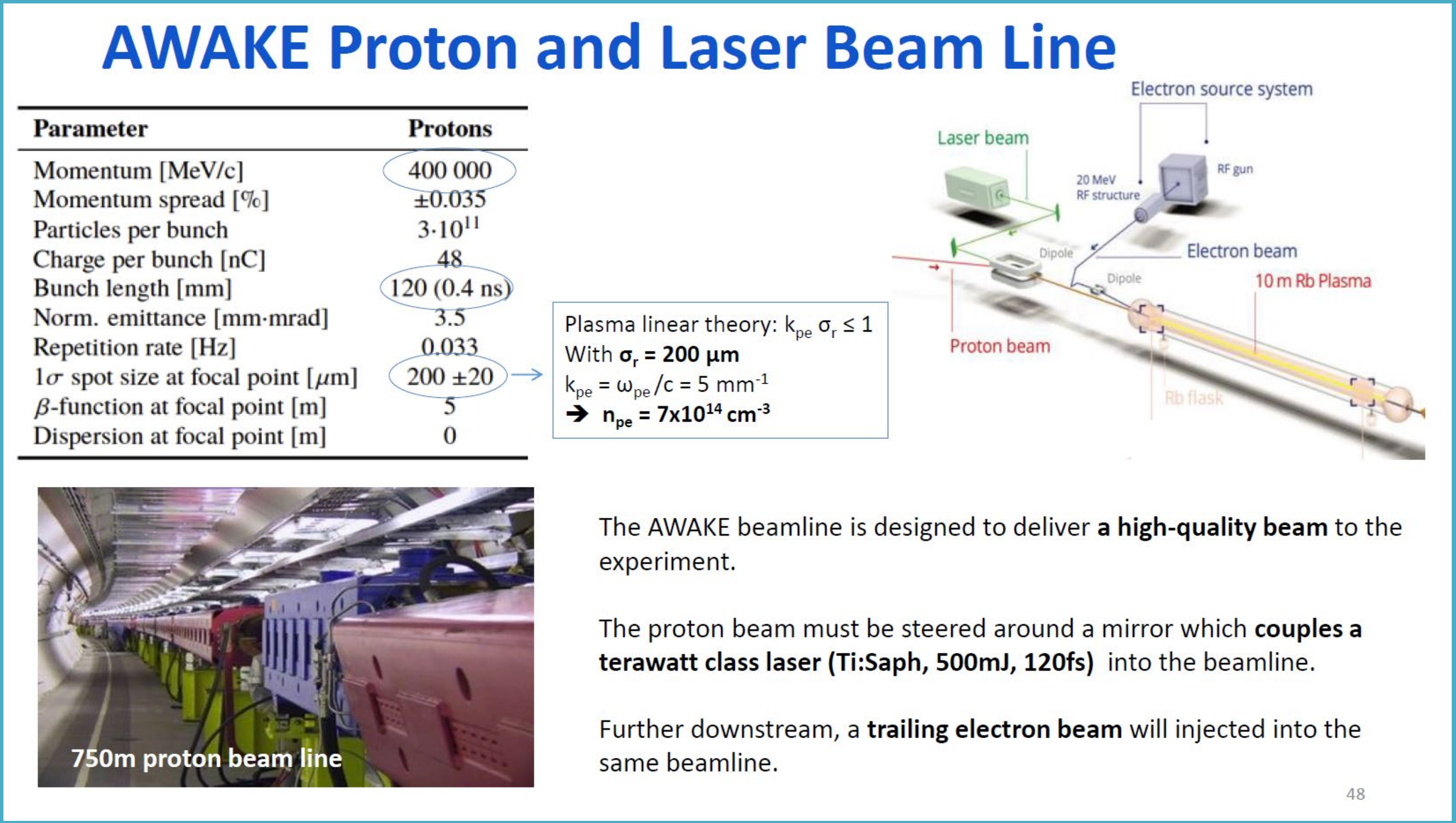
Run 1 Completed
After LS2 – proposing Run 2 of AWAKE
After Run 2 – kick off particle physics driven applications

AWAKE Run 1 Layout



AWAKE Experiment

AWAKE Beamlines



AWAKE Proton and Laser 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

Plasma linear theory: $k_{pe}\,\sigma_r \leq 1$
With $\boldsymbol{\sigma_r = 200\ \mu m}$
$k_{pe} = \omega_{pe}/c = 5\ mm^{-1}$
➔ $\mathbf{n_{pe} = 7x10^{14}\ cm^{-3}}$

The AWAKE beamline is designed to deliver **a high-quality beam** to the experiment.

The proton beam must be steered around a mirror which **couples a terawatt class laser (Ti:Saph, 500mJ, 120fs)** into the beamline.

Further downstream, a **trailing electron beam** will injected into the same beamline.

AWAKE Vapor Source

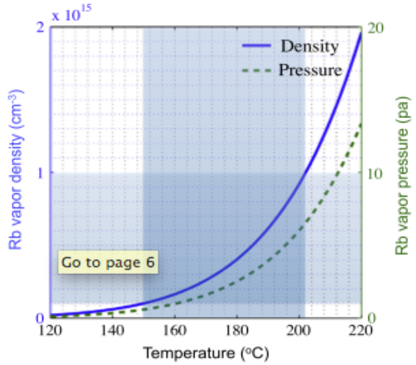
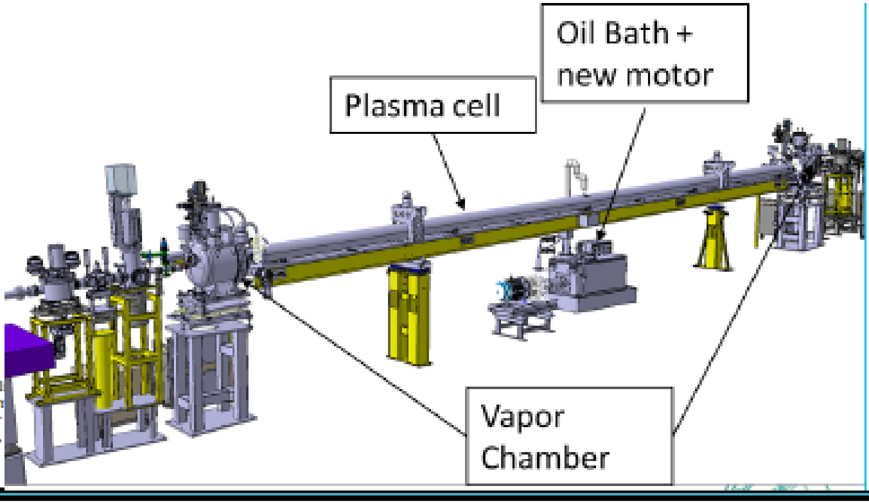
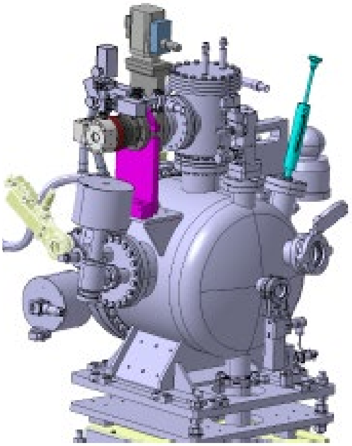
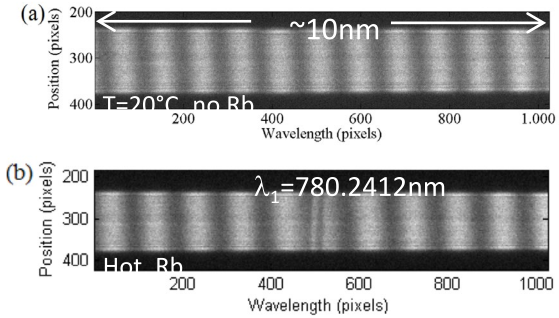
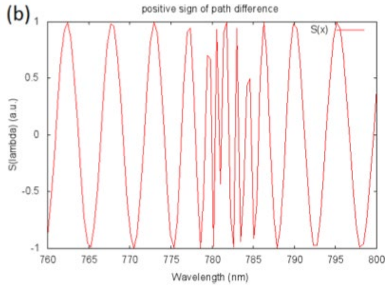


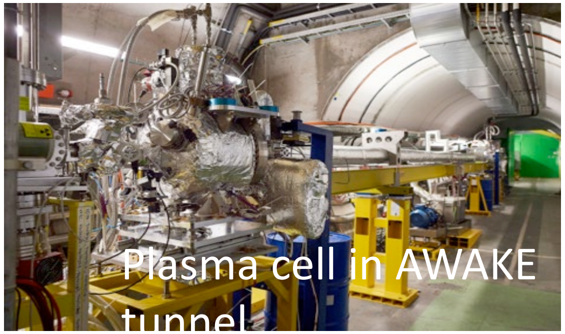
Fig. 1. Rubidium vapor density (blue line) and vapor pressure (green dashed l
as a function of temperature. Region between 1×10^{14} cm^{-3} and 1×10^{15} cm
and the corresponding temperature show the parameter range of interest for
PDPWFA. (For interpretation of the references to color in this figure caption,
reader is referred to the web version of this article.)







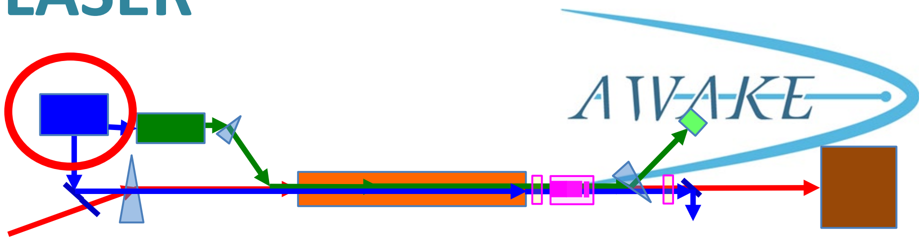




- 10 meter rubidium vapor source
- Rubidium is controlled to within .2% neutral density, gradients can be controlled (1-10) e14/cm^3
- Rubidium neutral density is measured by white light interferometry

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

TW LASER



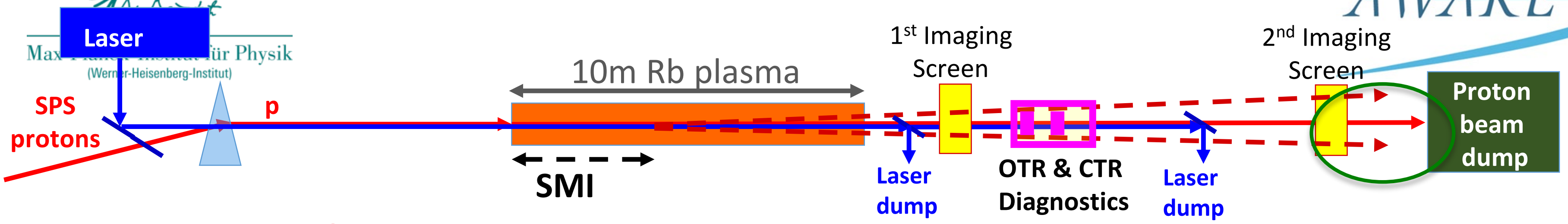

Laser Room at AWAKE

Laser System	
Laser type	Er:Fiber/ OscillatorTi:Sapphire
Pulse wavelength	λ_0 = 780 nm
Pulse length	120 fs FWHM
Maximum Pulse energy (after compressor)	**450 mJ**
Maximum Laser power	**4.5 TW**
Focused laser size	**$\sigma_{x,y}$ = 1 mm**
Rayleigh length Z_R	~3.5 m
Energy stability	±1.5% r.m.s.
Repetition rate	10 Hz

Amplitude
Technologies
Centarus X

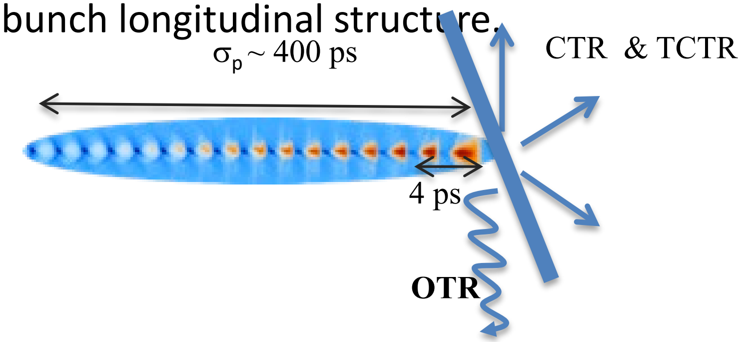
- Fiber laser chosen for stability on long runs
- Laser BW is only 15nm with peak spectrum at 780nm
- Several Rb lines within spectrum

AWAKE SSM Diagnostics



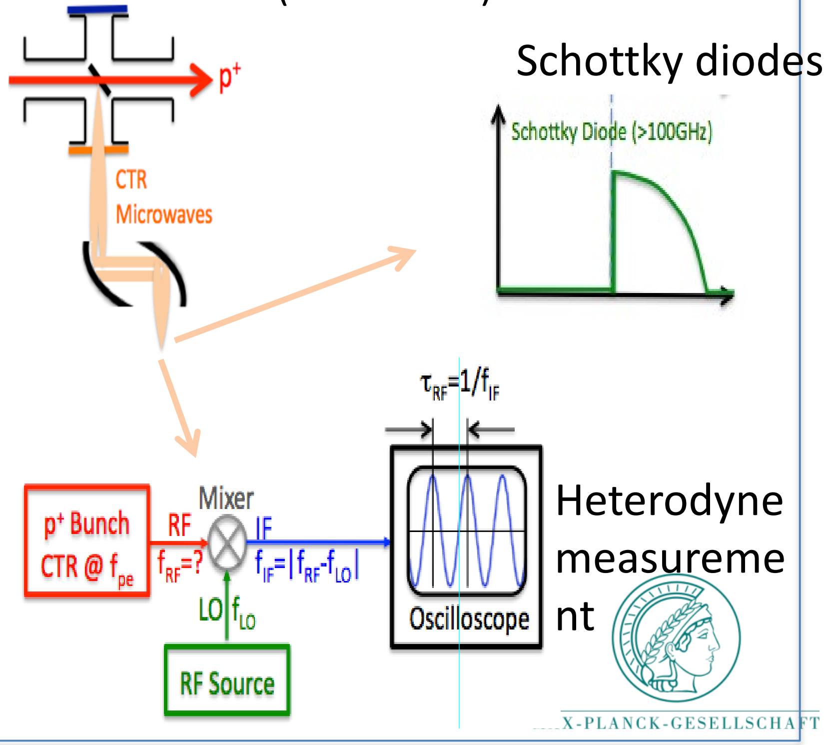
Direct SSM diagnostic: **Measure frequency of modulation.**

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



Streak Camera

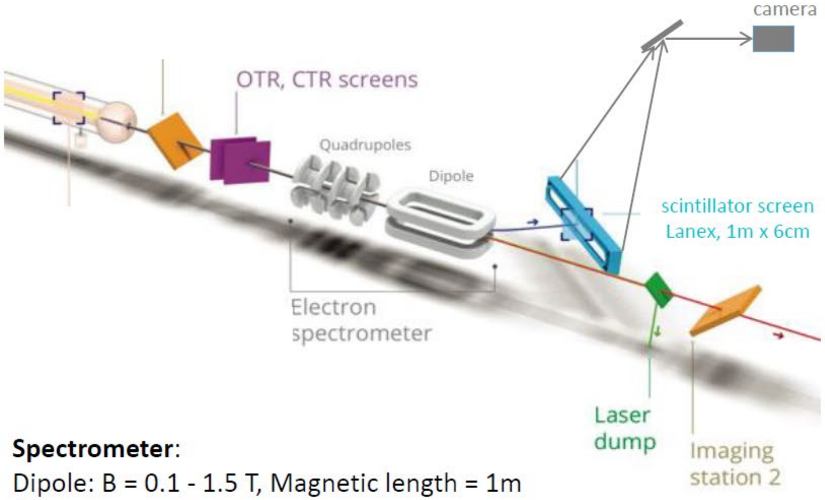
CTR: Coherent Transition Radiation: Radiation is coherent for wavelengths bigger than the structure of the micro-bunches (90-300GHz).



Schottky diodes

Heterodyne measurement

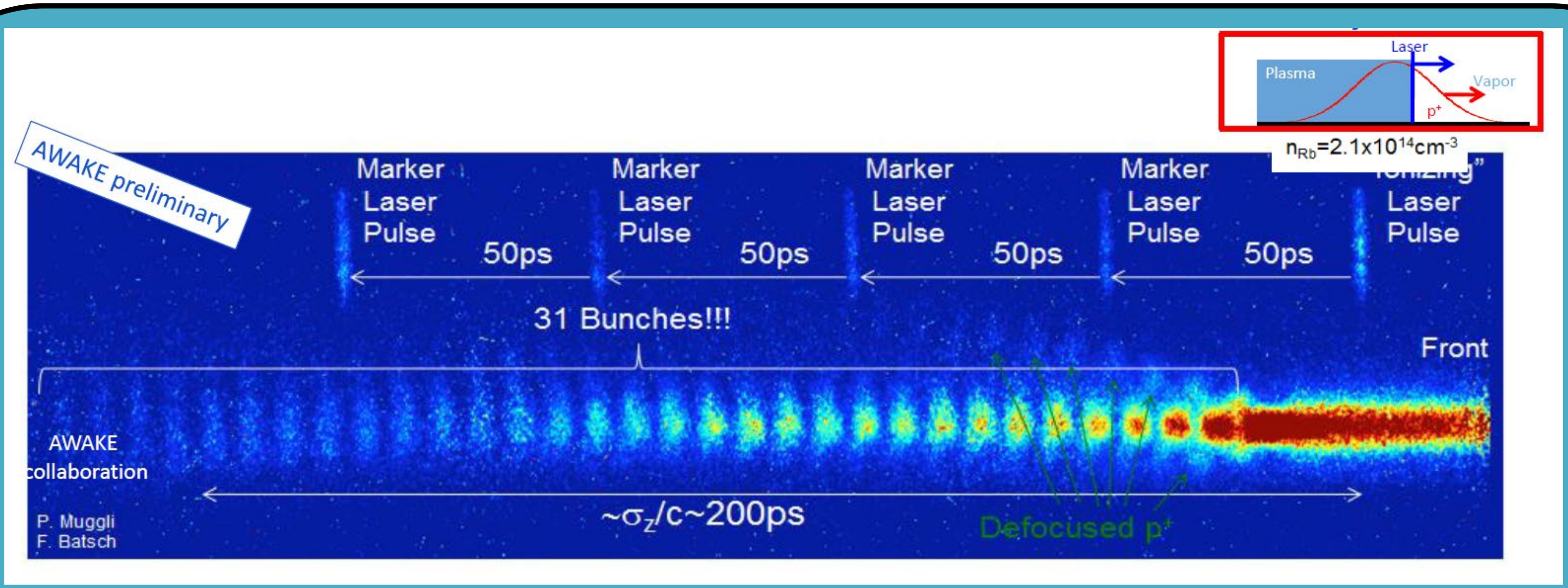
Acceleration Diagnostic: Spectrometer



Spectrometer:
Dipole: B = 0.1 - 1.5 T, Magnetic length = 1m
→ detect electrons with energies ranging from 30MeV - 8.5 GeV

Spectrometer

AWAKE Run 1 Results: Seeded Self Modulation

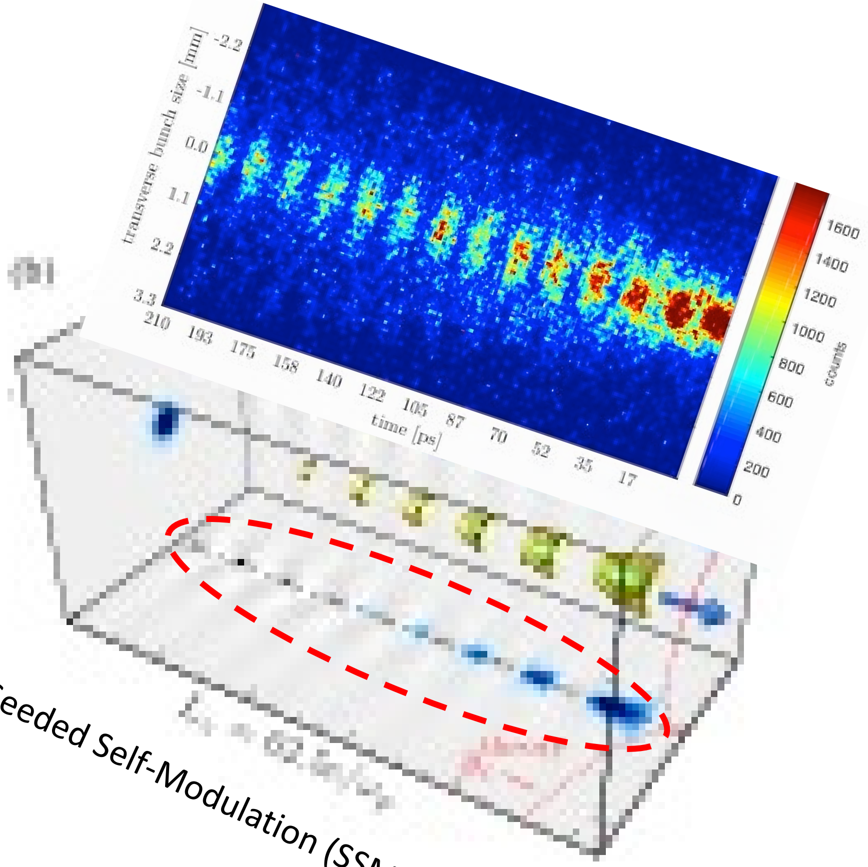


Demonstration of Seeded Self Modulation

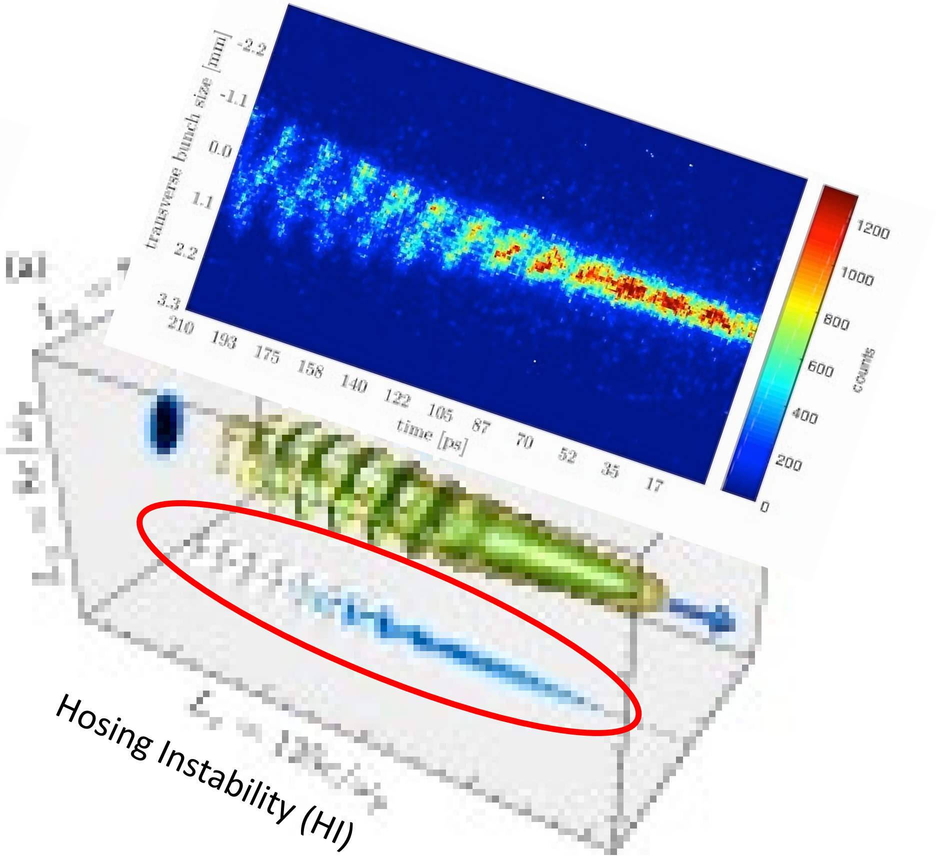
Seeding the self modulation of the proton demonstrates phase stability which is required for stable injection of the witness beam after wakefields have grown!

Hosing Instability

✧Self-modulation (SMI, SSM) cylindrically symmetric (2D)



Seeded Self-Modulation (SSM)



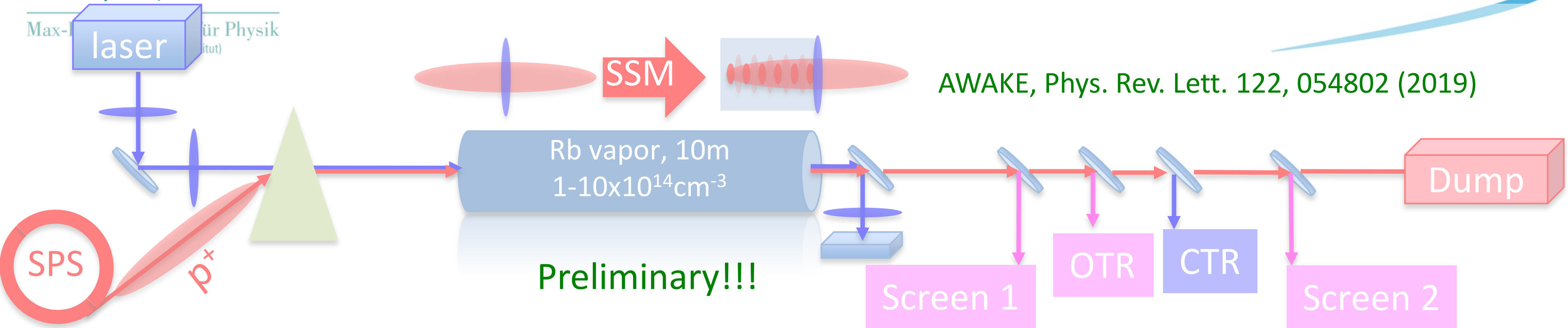
Hosing Instability (HI)

✧Hosing instability within frequency ω_{pe}

✧Observed only with low n_{e0}

J. Vieira et al., Phys. Rev. Lett. 112, 205001 (2014).

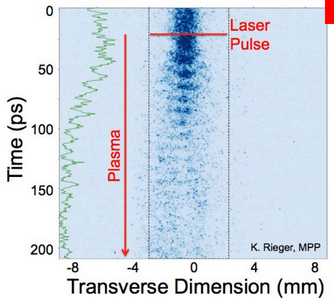
SSM Frequency

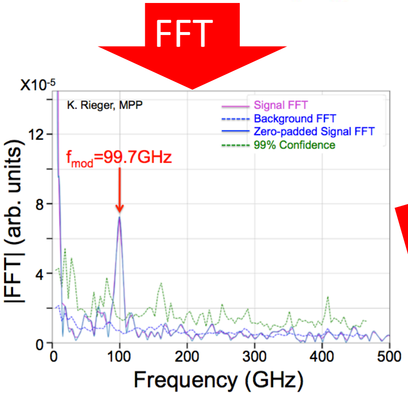


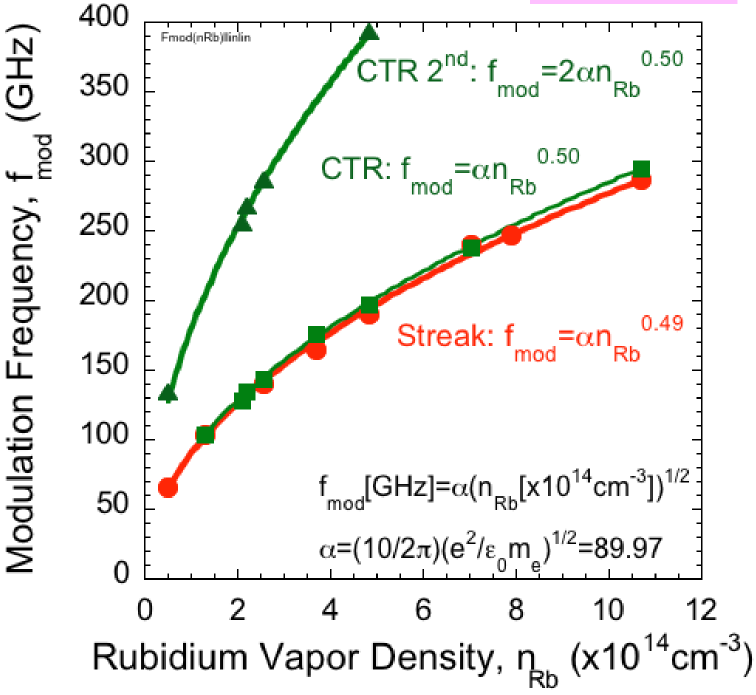
AWAKE, Phys. Rev. Lett. 122, 054802 (2019)

Preliminary!!!

OTR

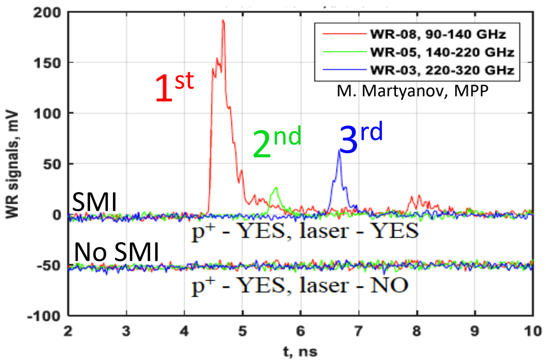






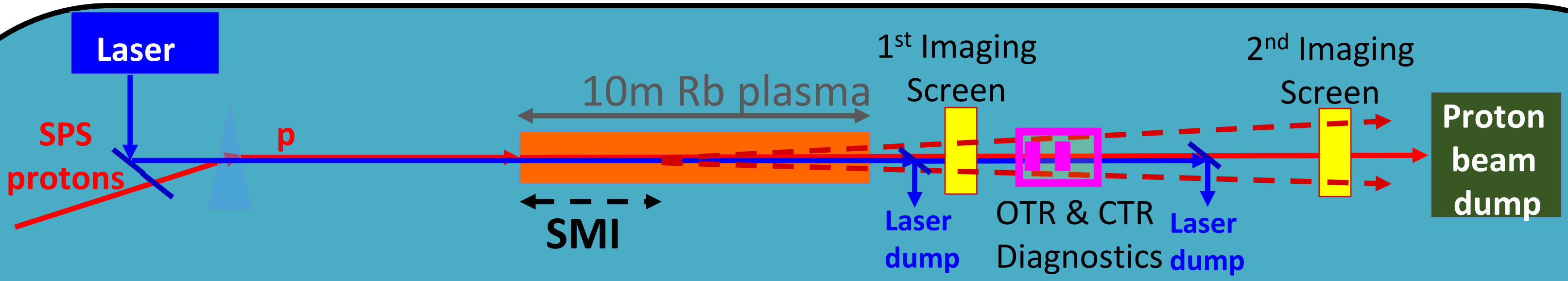
CTR

K. Rieger
M. Martyanov,
F. Braunmueller, MPP

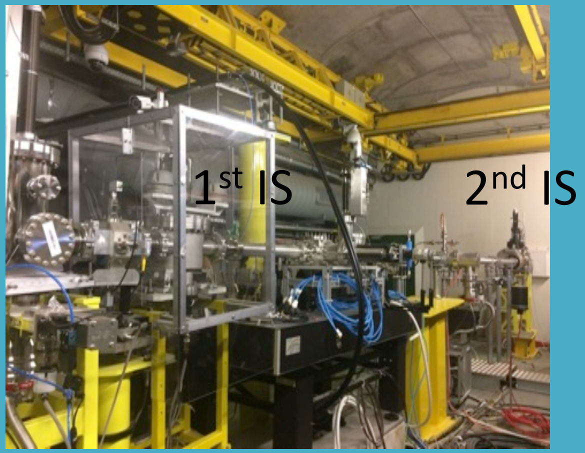


- ✧ $f_{mod} \sim n_{Rb} \rightarrow n_e = n_{Rb}$ ionization and $f_{mod} \sim f_{pe}$
- ✧ CTR signal detected at harmonics (not calibrated)
- ✧ Modulation is nonlinear

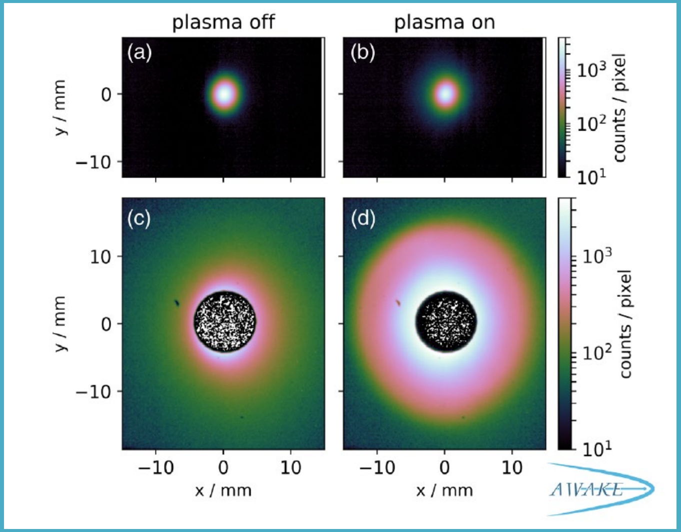
Indirect Measurement of SSM



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



M. Turner, CERN



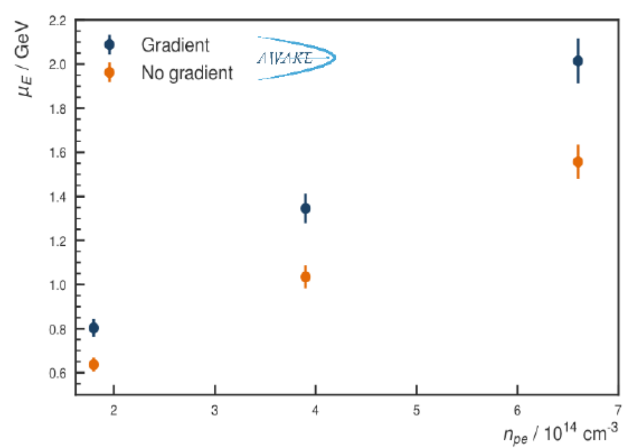
M. Turner et al PRL

Two imaging stations (IS) to measure the **radial proton beam distribution** 2 and 10 m downstream the end of the plasma.

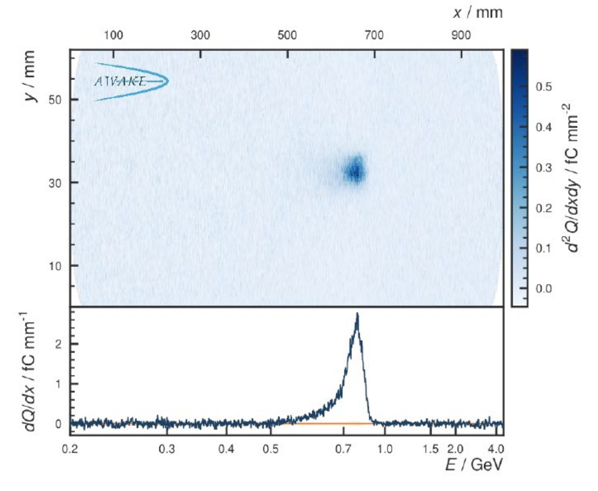
→ Growth of tails governed by transverse fields in the plasma.

AWAKE Run 1 Results: Acceleration

Demonstration of electron acceleration



Demonstrated energy gain up to 2 GeV

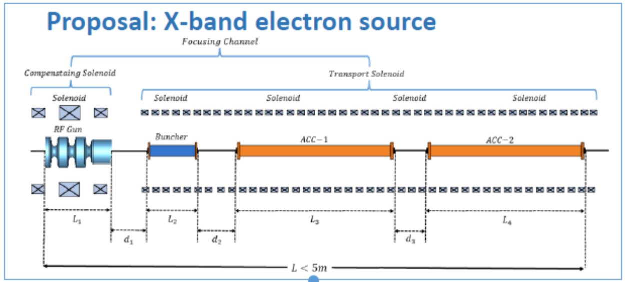


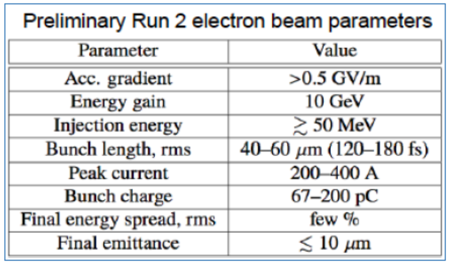
Sample event at 2e14/cm^3
Yielding 700 MeV

AWAKE Run 2

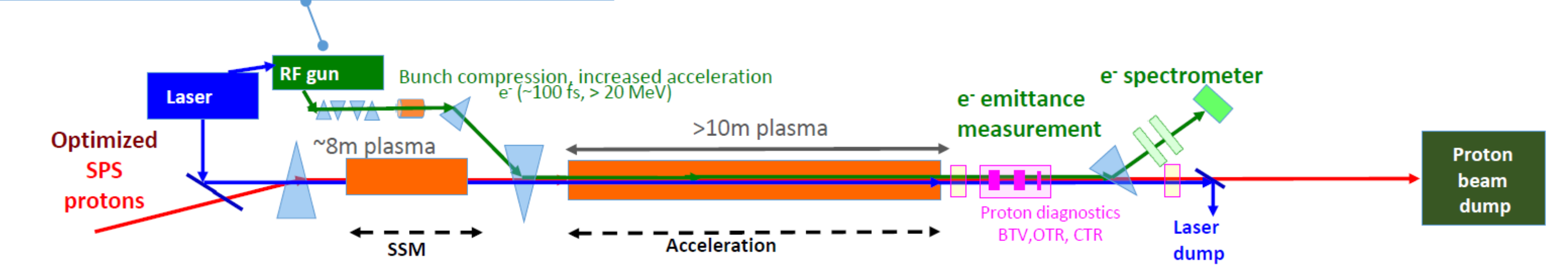
Goals for Run 2

- **Accelerate an electron beam to high energy** (gradient of 0.5-1GV/m)
- **Preserve electron beam quality** as well as possible (emittance preservation at 10 mm mrad level)
- **Demonstrate scalability** of the AWAKE concept (R&D plasma sources)


Proposal: X-band electron source

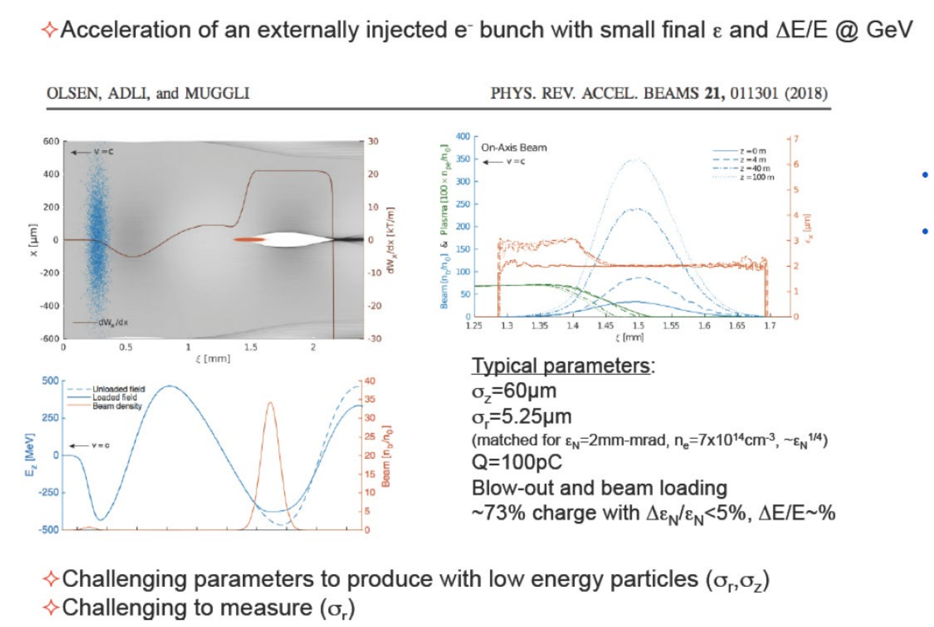

Preliminary Run 2 electron beam parameters

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



AWAKE Run 2:
Demonstration of Beam Preservation

- For Run 2 AWAKE must demonstrate high beam quality of the accelerated beam
- This means low energy spread and low emittance



✧Acceleration of an externally injected e⁻ bunch with small final ε and ΔE/E @ GeV

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

Typical parameters:

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%, ΔE/E~%

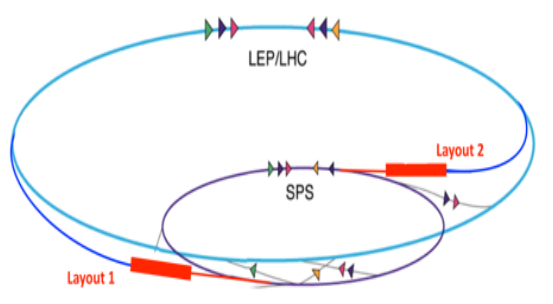
✧Challenging parameters to produce with low energy particles (σ_r,σ_z)

✧Challenging to measure (σ_r)

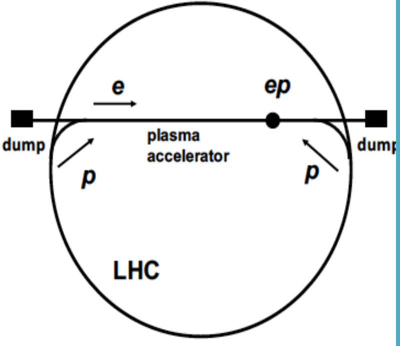
Beyond Run 2: Applications for AWAKE

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

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



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



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

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

Conclusions for AWAKE

- AWAKE is proton driven plasma wakefield experiment at CERN
- Aim of AWAKE: accelerating electrons with ~1 GV/m gradient using seeded self-modulation of a long proton bunch in a plasma ($\sigma_z >> \lambda_{pe}$)
- First Seeded Self-Modulation measurements in 2016/17
  - The Seeded Self-Modulation of the proton beam has been observed.
- Electron acceleration in the plasma wakefield: Observed energy gain up to 2 GeV
- Run 2 is proposed for after 2020: preserve electron beam quality, scalability
  - Will split into SSM and accelerating stages
- First studies on applications of p-driven PWFA up at 10's of GeV and TeV scales are currently under investigation

MAX-PLANCK-GESELLSCHAFT