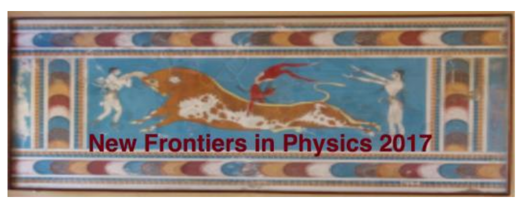
AWAKE: the proton-driven plasma wakefield accelerator experiment at CERN

Erik Adli

Department of Physics, University of Oslo, Norway

on behalf of the AWAKE collaboration



6h International Conference on New Frontiers in Physics

August 28, 2017, OAC, Crete, Greece

AWAKE

- AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment
  - Use CERN SPS proton beam as drive beam (Single bunch 3e11 protons at 400 GeV)
  - Inject electron beam as witness beam

- Proof-of-Principle Accelerator R&D experiment at CERN
  - First proton driven plasma wakefield experiment worldwide

- AWAKE Collaboration: 18 institutes world-wide:

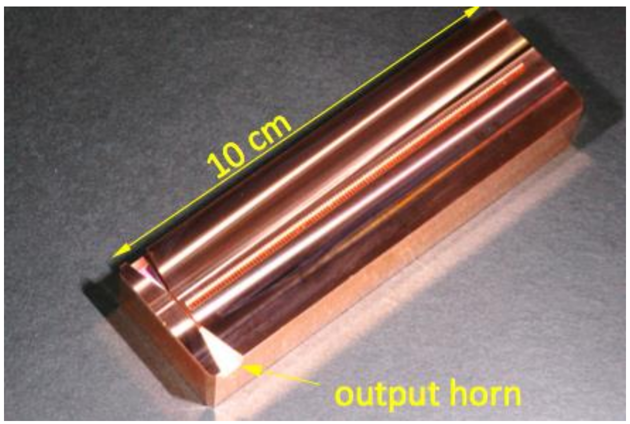
John Adams Institute for Accelerator Science,
Budker Institute of Nuclear Physics & Novosibirsk State University
CERN
Cockroft Institute
DESY
Heinrich Heine University, Düsseldorf
Instituto Superior Tecnico
Imperial College
Ludwig Maximilian University
Max Planck Institute for Physics
Max Planck Institute for Plasma Physics
Rutherford Appleton Laboratory
TRIUMF
University College London
Univesity of Oslo
University of Strathclyde
UNIST, Korea
University of Marburg

Advanced accelerator research

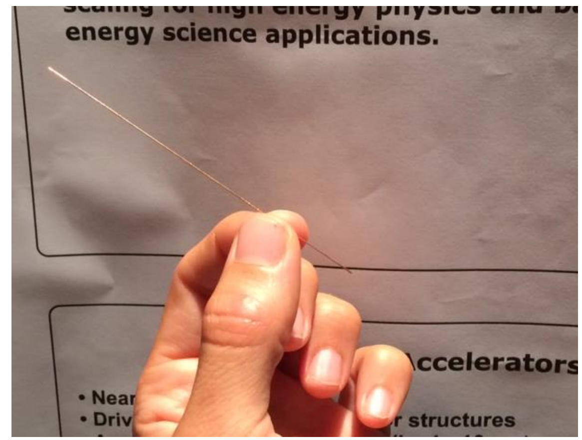
Research in new accelerator principles, with objective of **overcoming accelerating gradient limitations** of RF technology. Promise for more compact accelerators.

Very high frequency normal conducting rf structures (~100 GHz to ~THz)

116 GHz structure (SLAC)



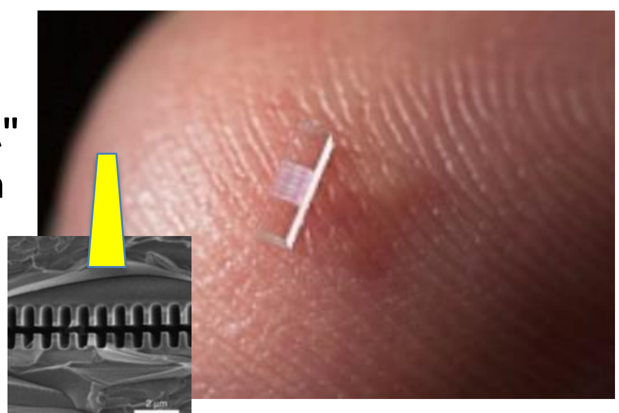
Dielectric structures

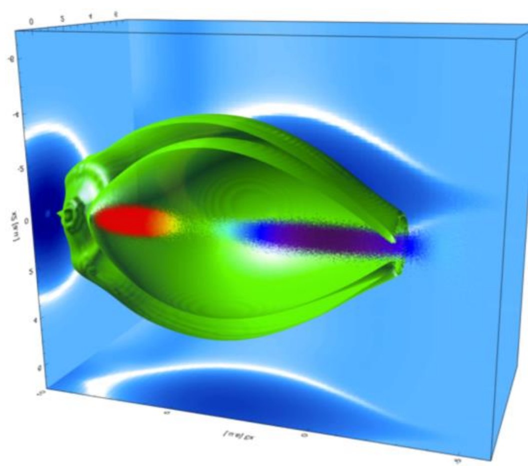


SiO_2

~ 1.0 THz, Accelerating fields of 300 MV/m demonstrated

Laser based acceleration "DLA"
Several 100 MV/m demonstrated (SLAC)



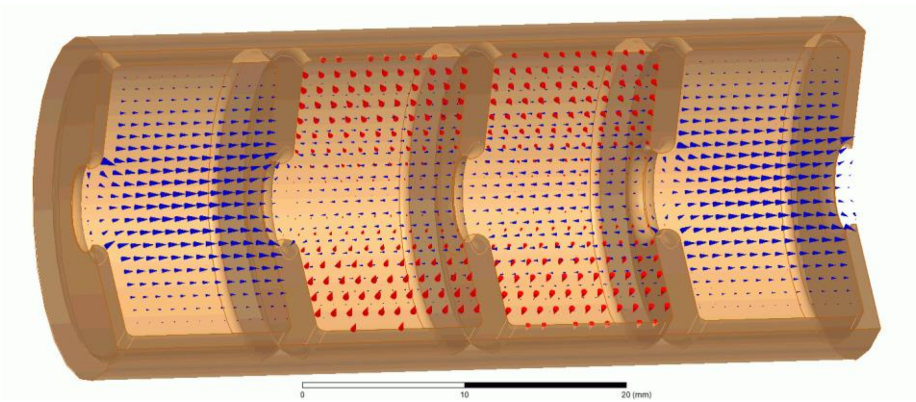


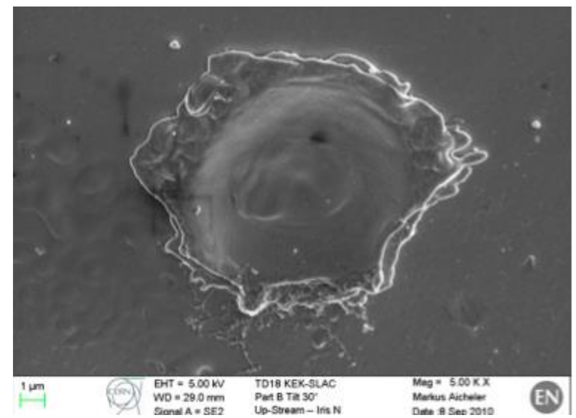
Plasma wakefield acceleration

The topic of this talk

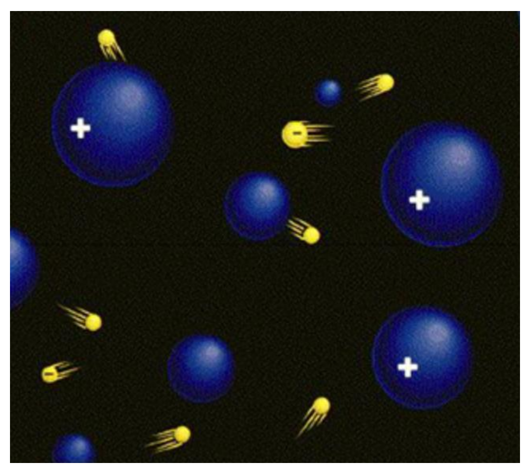
Breakdown limits and plasma

In **metallic structures** a too high field level will break down the surfaces, creating electric discharges. Field cannot be sustained. Structures may be damaged. **Current practical limit (CLIC): order of 100 MV/m accelerating field**.





A plasma: collection of free positive and negative charges (ions and electrons). Material is already broken down. A plasma can therefore **sustain very high fields.**



Estimation of plasma wave field amplitude

Assume that the plasma electrons are pushed out of a small volume of neutral plasma, with plasma density $n_0 = n_e = n_{ion}$:

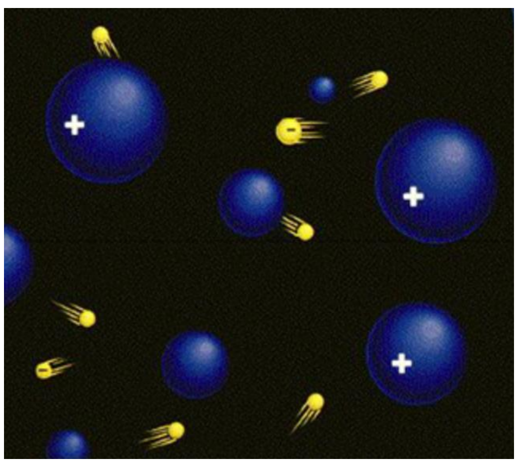
Scale of electrical fields (1D) :

Gauss' law:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \sim \frac{e n_{\text{ions}}}{\varepsilon_0} \sim \frac{e n_0}{\varepsilon_0}$$

Plasma electron frequency :

$$\omega_p = \sqrt{\frac{n_0 e^2}{m_e \varepsilon_0}}$$



Assume wave solutions:

$$\mathbf{E} \sim \mathbf{E_0} \exp(-i\omega_p / cz)$$

Apply Gauss' law:

$$\frac{e n_0}{\varepsilon_0} = E_0 \frac{\omega_p}{c} \Rightarrow E_{WB} = \frac{e c n_0}{\varepsilon \omega_{0p}} \sim \sqrt{n_0}$$

Field scale, E_{WB}
"wave breaking field"

Example of neutral plasma density used for experiments :

$\mathbf{n_0} \sim 1e15/cm^3$: $\mathbf{E_{WB} = 3\ GV/m}$

Plasma wakefield acceleration (PWA)

An intense **particle beam**, or intense **laser beam**, can be used to drive the plasma electrons.

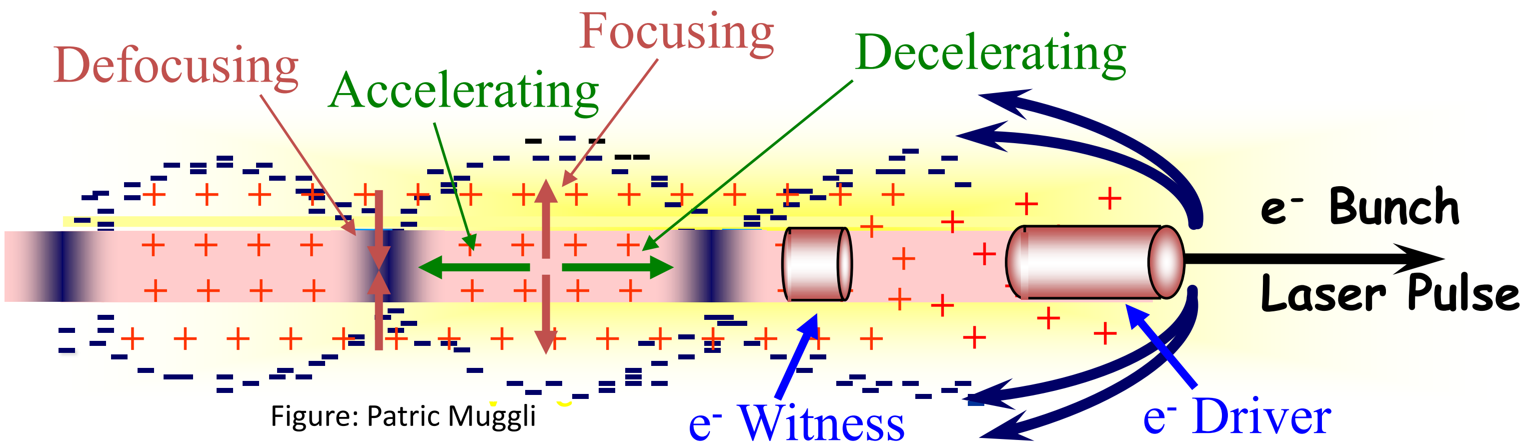


Figure: Patric Muggli

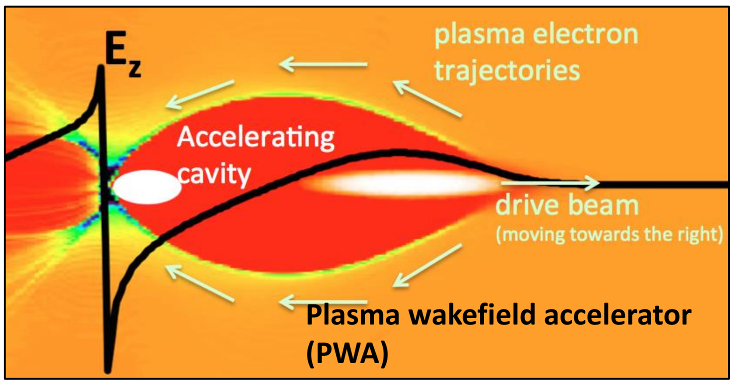
Typical plasma densities used in experiment, 10^{14}-10^{20}/cm^3, **For $n_0 \sim 10^{15}$/cm^3 :**

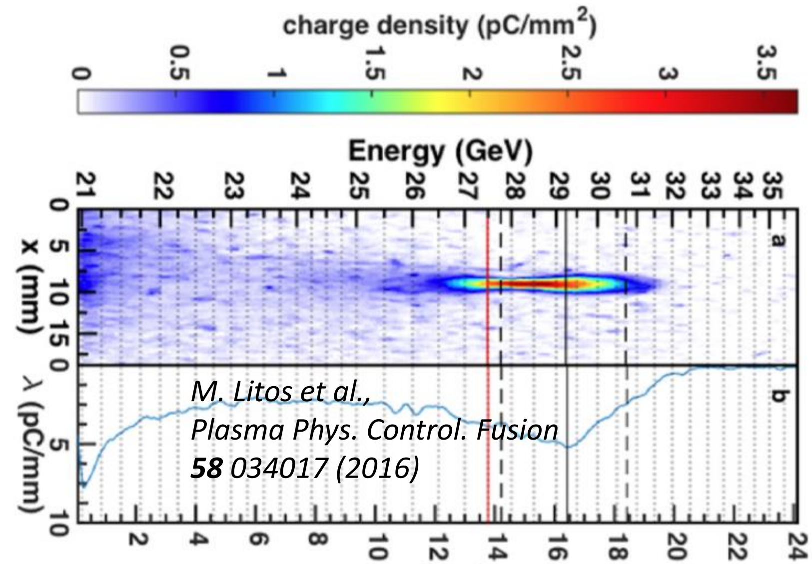
- **Field scale:** E_{WB} = **3 GV/m** ~ $\sqrt{n_0}$
- **Length scale :** $k_p^{-1}=\lambda_{pe}/2\pi=$**1 mm** ~ $\sqrt{n_0}$, plasma skin-depth $k_p^{-1}=c\,/\,\omega_{pe}$
- **Radial focusing :** $F_r/c=\frac{1}{2}en_0r/\varepsilon_0=$**30 kT/m**

Ideas of **~100 GV/m** electric fields in plasma, using 10^{18} W/cm^2 lasers: 1979 **T.Tajima and J.M.Dawson** (UCLA), Laser Electron Accelerator, Phys. Rev. Lett. 43, 267–270 (1979).
Using partice beams as drivers: **P. Chen et al**. Phys. Rev. Lett. 54, 693–696 (1985)

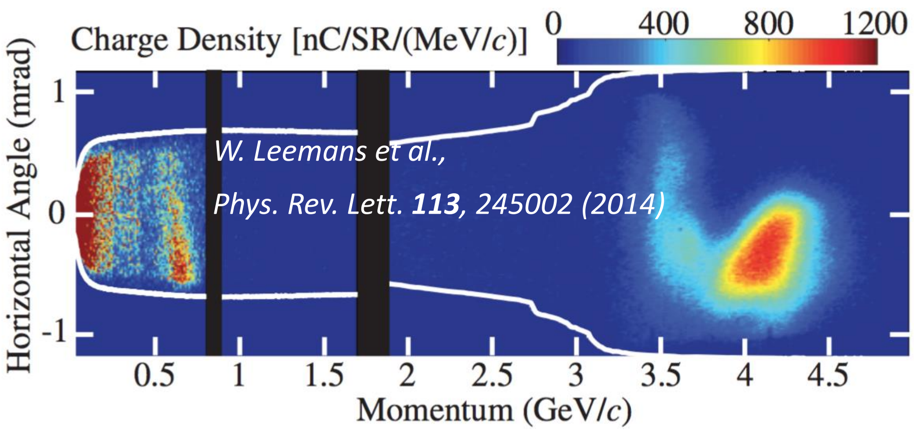
Recent experiment progress in PWA

Acceleration of beams to **GeV-energies** in plasmas has recently **been demonstrated**, using laser beams, electron beam and positron beams as drivers.





GeV-energy gain in 1.3 m beam-driven PWA

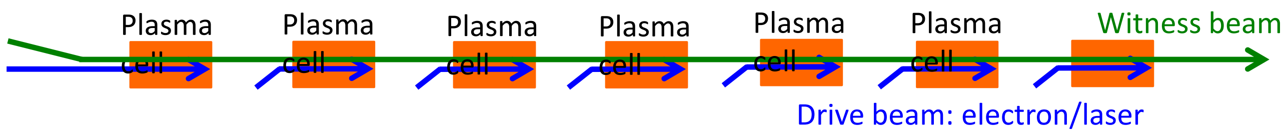


GeV-energy gain in 9 cm laser-driven PWA

Challenge: towards TeV

Towards TeV beams

While GeV acceleration in plasmas has been demonstrated for with both lasers and electron beams, reaching TeV scales requires **staging** of many drivers and plasma cells. **Challenging.**

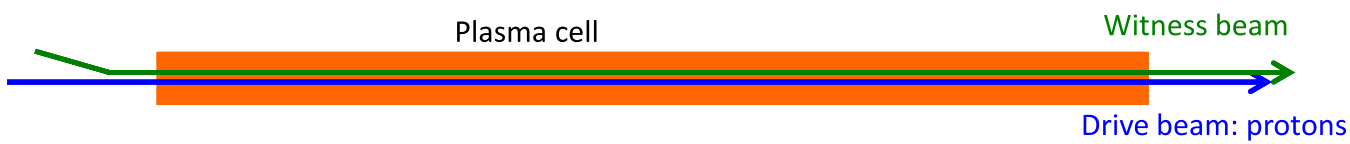


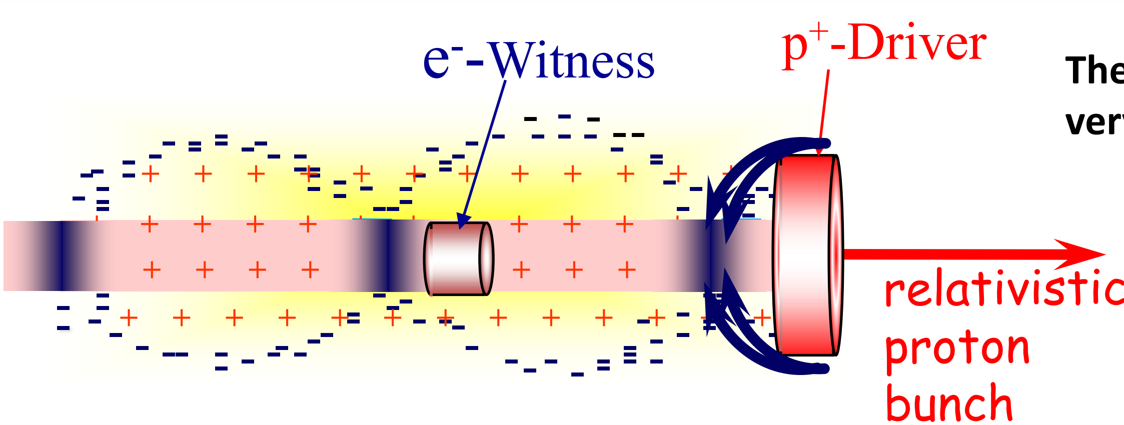
A possible witness beams:
Electrons: 10^{10} particles @ 1 TeV
~few kJ

Existing driver beams options :
Lasers: up to 40 J/pulse
Electron driver: up to 60 J/bunch
Proton driver: **SPS 19 kJ/bunch**, LHC **300 kJ/bunch**

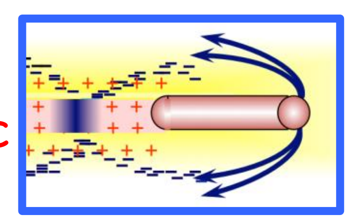
Proton drivers: large energy in proton bunches → can consider **single stage TeV acceleration**:

- A single SPS/LHC bunch could produce an ILC bunch in a single proton driven PWA stage.





The wake of short proton drivers ($\sim k_p^{-1}$) is very similar to that of electrons drivers.



The self-modulation instability

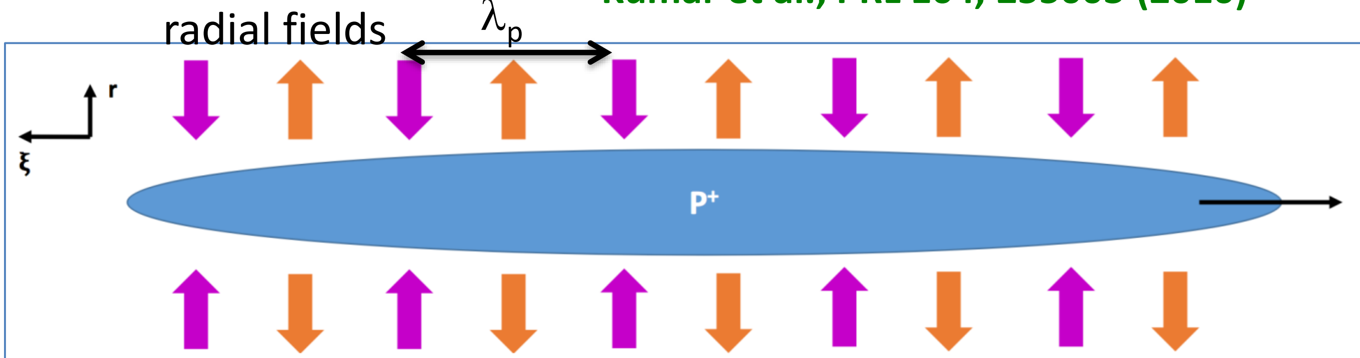
Available proton bunches at CERN are **10 – 30 cm long**; **λ_p for 7×10^{14} /cm^3 is 1.3 mm**. Wakes will be weak; linear regime.

The **radial fields** of the wake will modulate the beam density, creating **microbunches** spaced at the plasma wavelength.

The evolution of the radius depends on the radius; **self-modulation instability** (SMI).

The microbunches leads to **resonant build-up** of strong wake fields (of order GV/m).

Kumar et al., PRL 104, 255003 (2010)



$$W_\perp(r,\xi) = -4\pi\rho_0 \int_0^\xi r_b(\xi')I_1\{k_p r(\xi')\}K_1\{k_p r_b(\xi')\}f(\xi')\, k_p \sin k_p(\xi-\xi')d\xi',$$

Transverse force along the bunch

Focusing oscillates along bunch

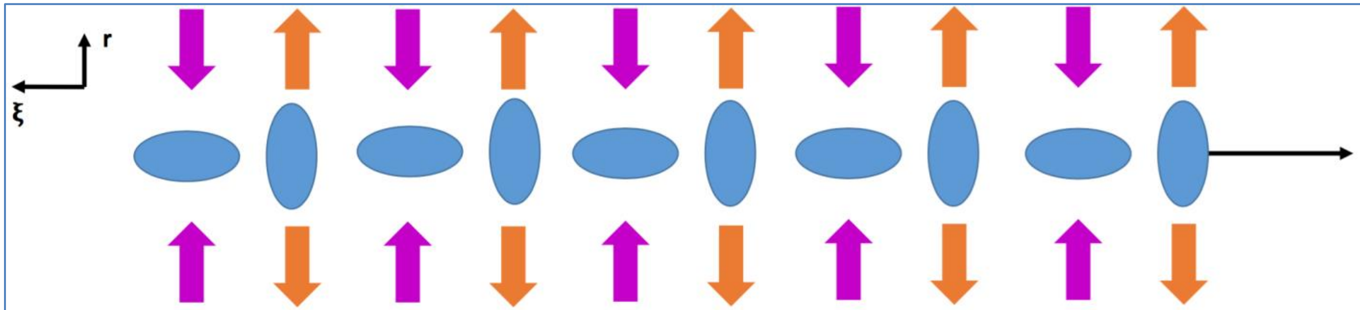


Figure: Spencer Gessner

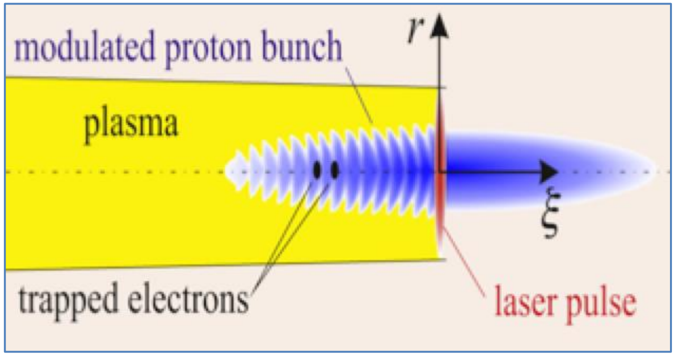
$$\frac{\partial^2 r_b}{\partial\tau^2} - \frac{\mathcal{M}^2}{r_b^3} = -\frac{\omega_b^2}{\gamma_0}\int_0^\xi r_b(\xi')I_1\{k_p r_b(\xi')\}K_1\{k_p r_b(\xi')\} f(\xi')\, k_p \sin k_p(\xi-\xi')d\xi',$$

Transverse beam size

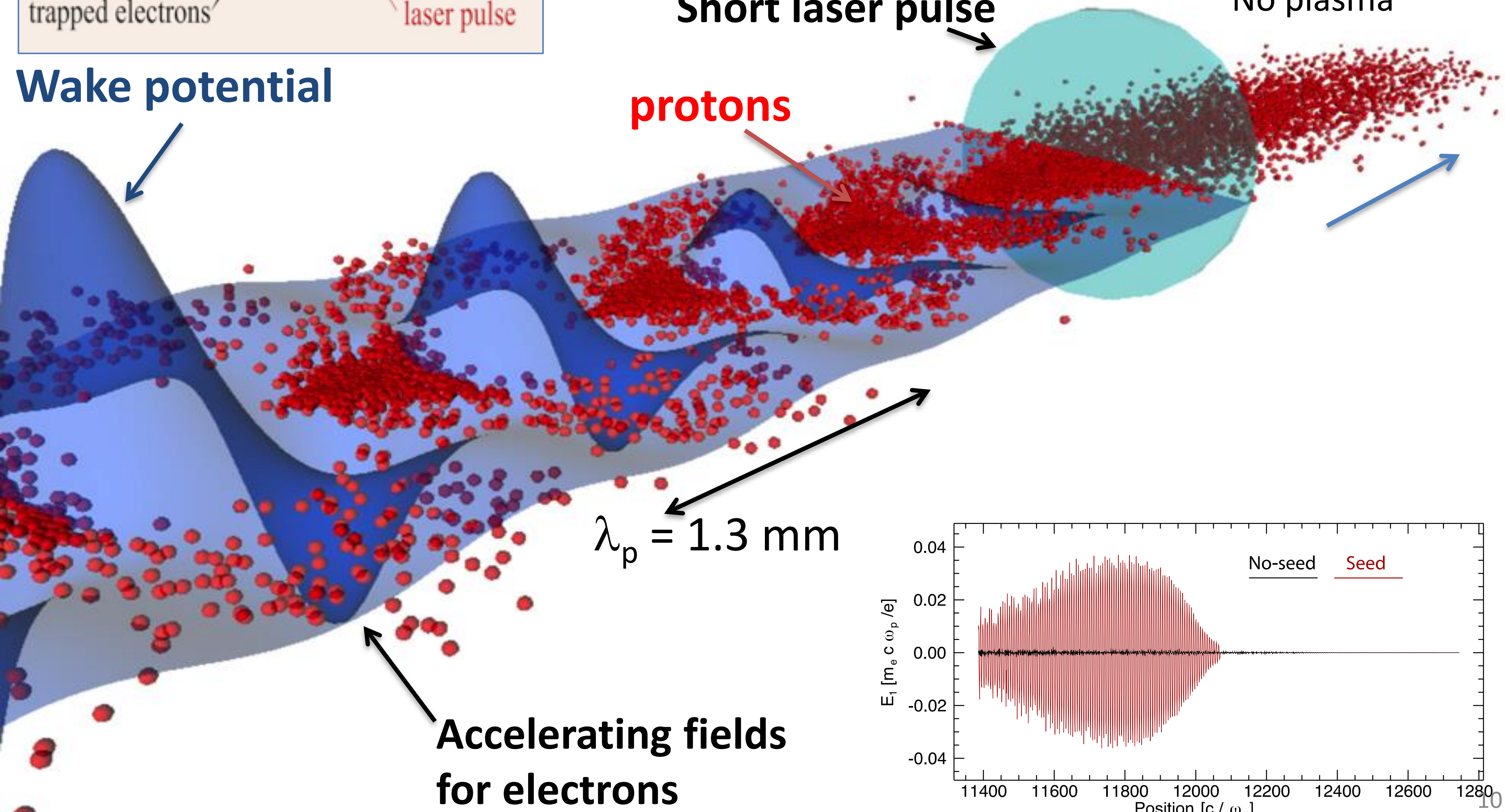
Radial beam evolution

Transverse force felt by bunch

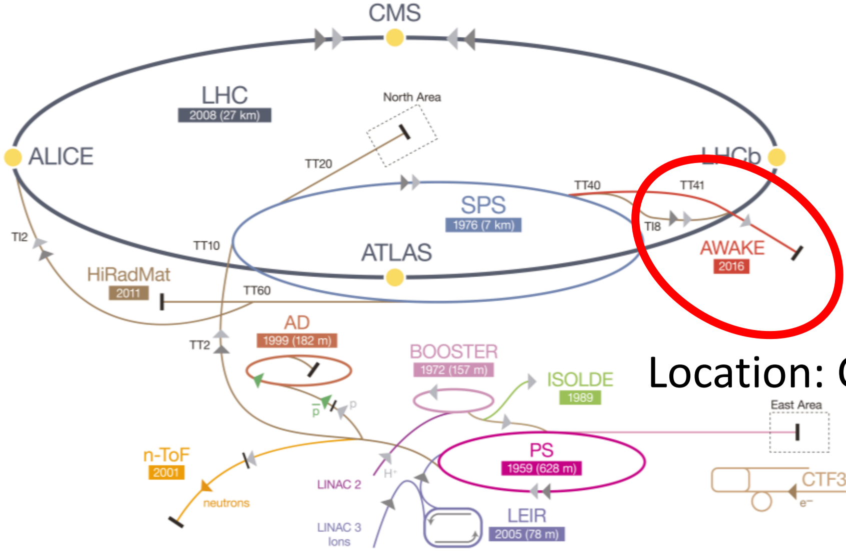
Seeded self-modulation instability



The self-modulation can be seeded by a sharp start of the beam (or beam-plasma interaction). Will be done by laser ionization front co-propagating with proton beam.

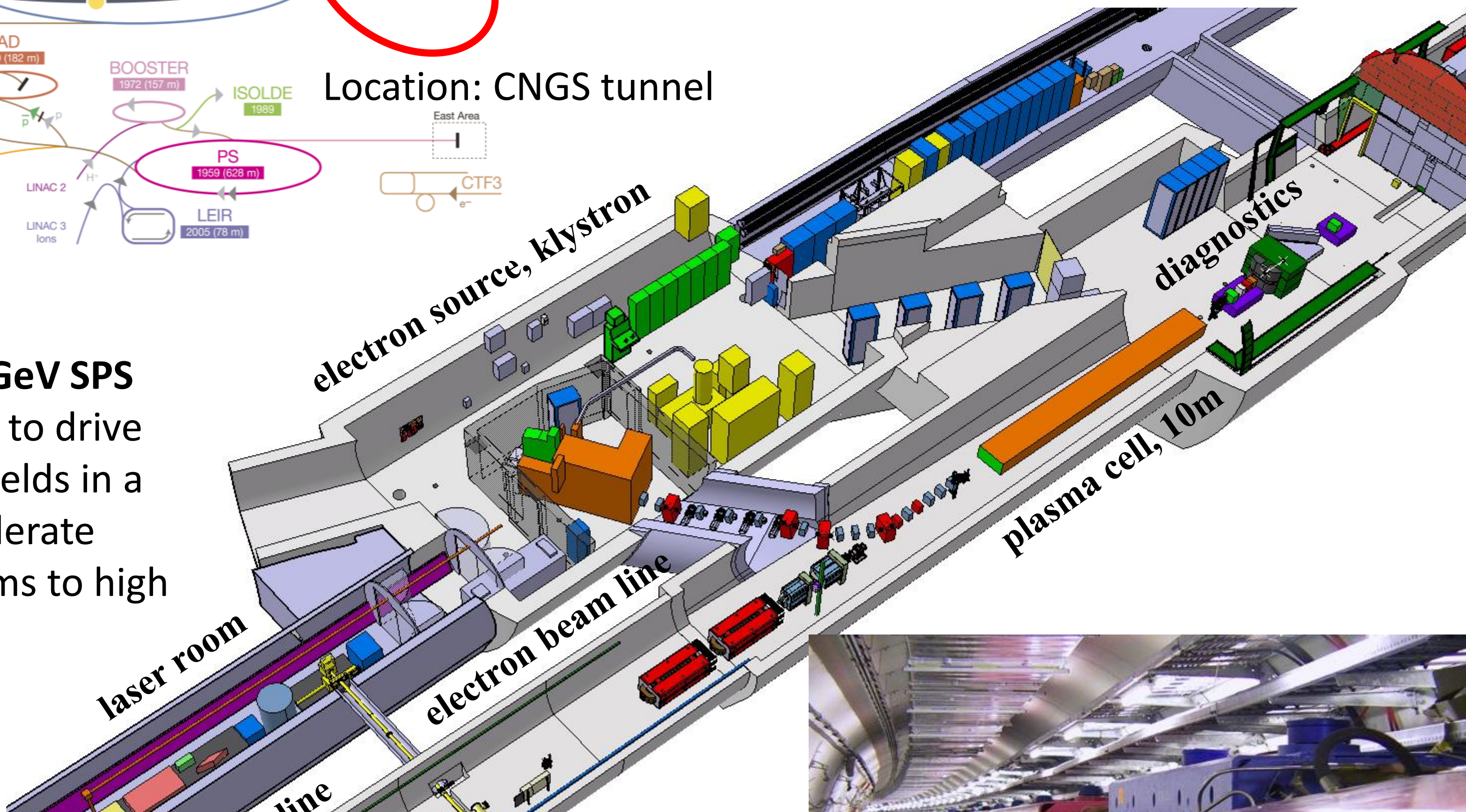


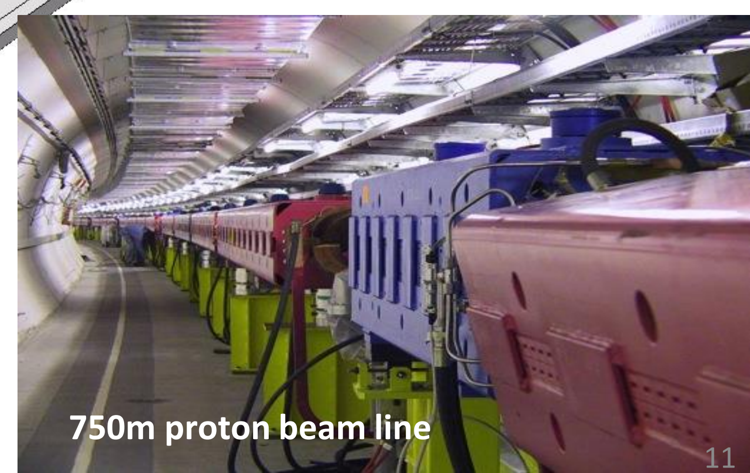
The AWAKE experiment at CERN



Location: CNGS tunnel

Use the **400 GeV SPS proton beam** to drive strong wakefields in a plasma. Accelerate electron beams to high energy.

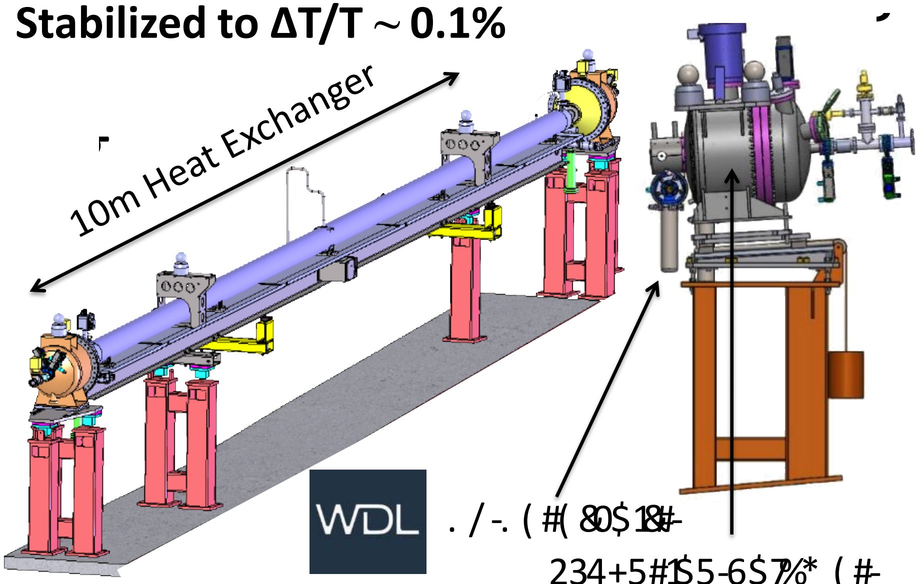


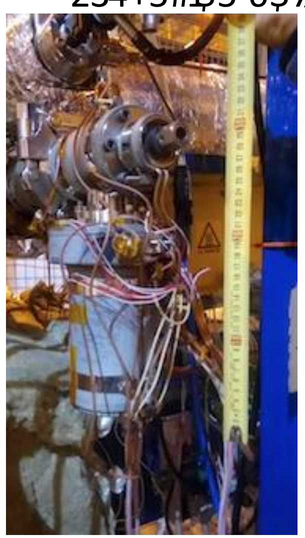


The 10 m AWAKE Rb vapour cell

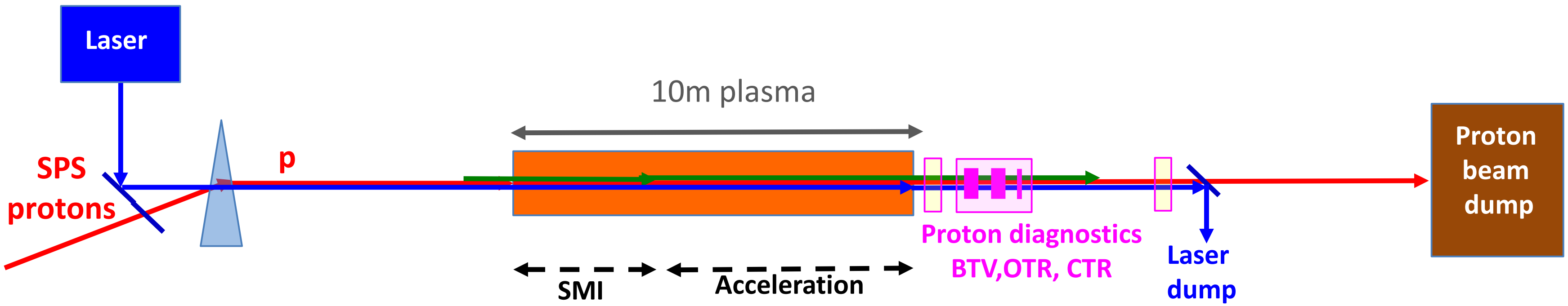
E. Oz and P. Muggli, Nucl. Instr. Meth. Phys. Res. A 740 (11) 197 (2014)

Stabilized to ΔT/T ~ 0.1%



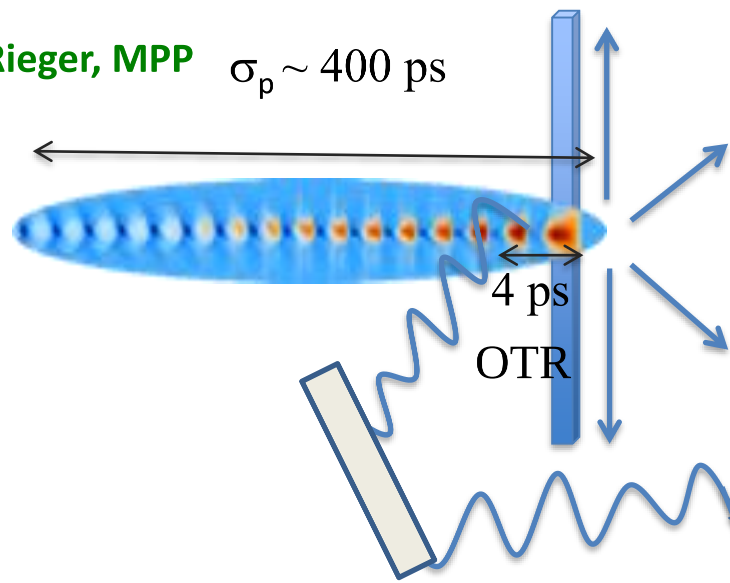


Phase 1 (2016-2017): study proton beam SMI

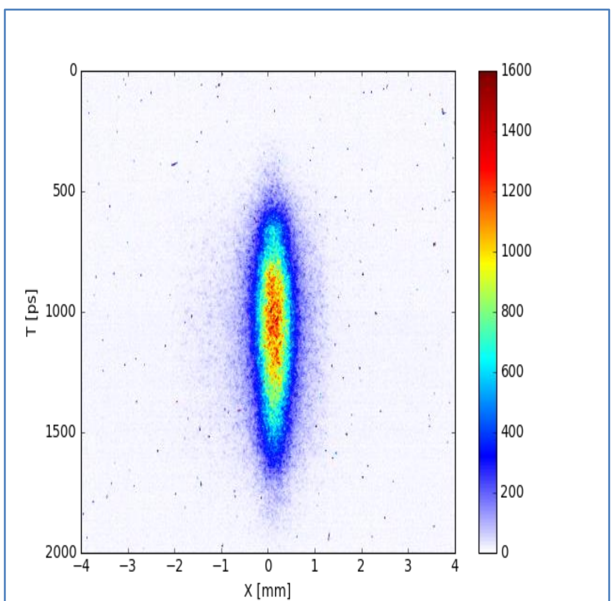


- **Goal:** understand **the physics of self-modulation instability** processes in plasma
- Hardware commissioned end 2016
- First experimental runs summer 2017. Data being analyzed
- **Preliminary** results following

SMI measurements I: streak camera



The modulated proton bunch is sent through a metal foil where it generates optical transition radiation **(OTR**). This radiation is sent to a **streak camera.**



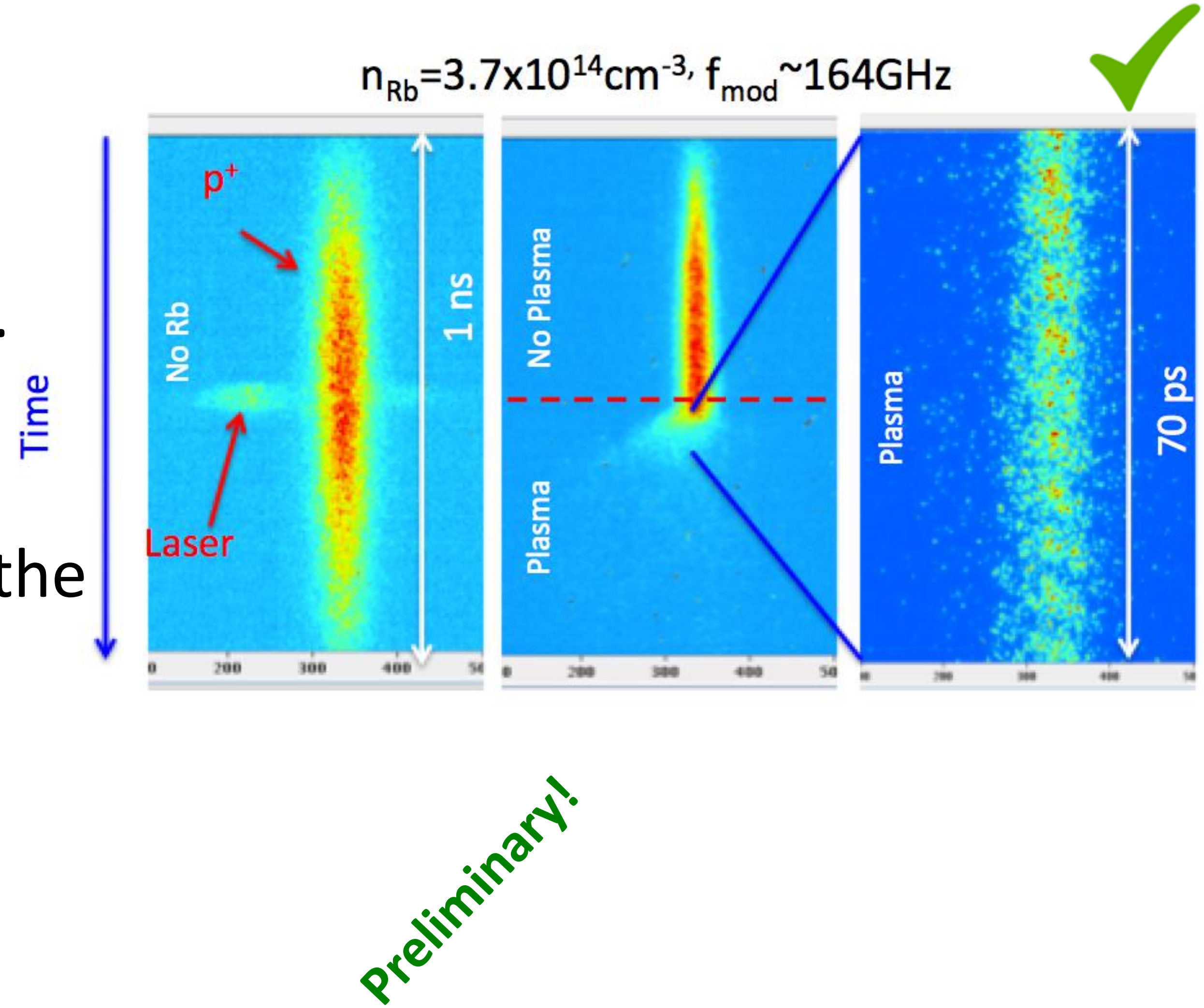
Left: the 12 cm SPS bunch as measured with the streak camera without plasma in the beamline. The bunch is typically straight with no visible structure.

Observation of Seeded SMI

The laser pulse ionizes the plasma about mid-way through the beam.

Observed microbunching at the seeded beam undergoes in the region trailing the plasma.

n_{Rb}=3.7x10^{14}cm^{-3}, f_{mod}~164GHz



K. Rieger, MPP

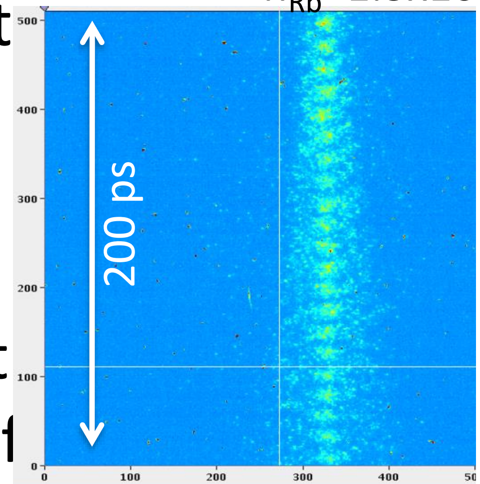
Observation of Seeded SMI

We observe strong, persistent microbunching for a range of densities.

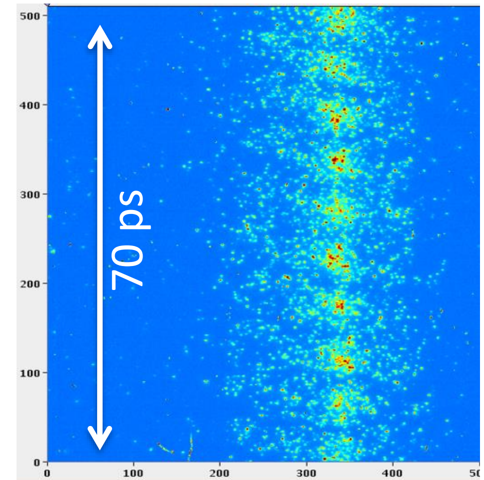
Seeding is a critical ingredient for producing many periods of microbunches along the beam.

Can do FFT of image to find modulation frequency.

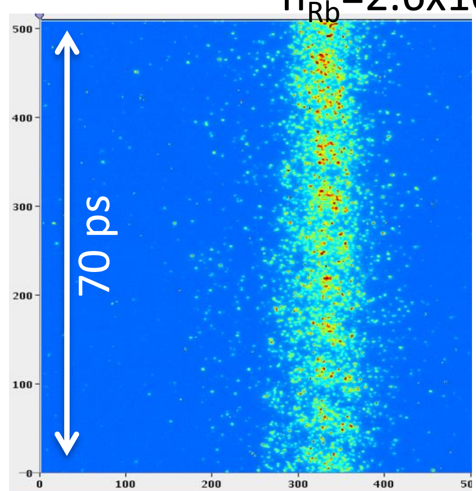
$n_{Rb}=1.3\times10^{14}cm^{-3}$



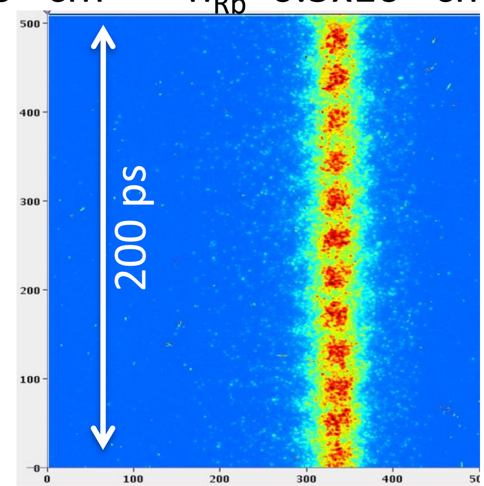
$n_{Rb}=2.0\times10^{14}cm^{-3}$



$n_{Rb}=2.6\times10^{14}cm^{-3}$



$n_{Rb}\approx0.5\times10^{14}cm^{-3}$



Preliminary!

K. Rieger, MPP

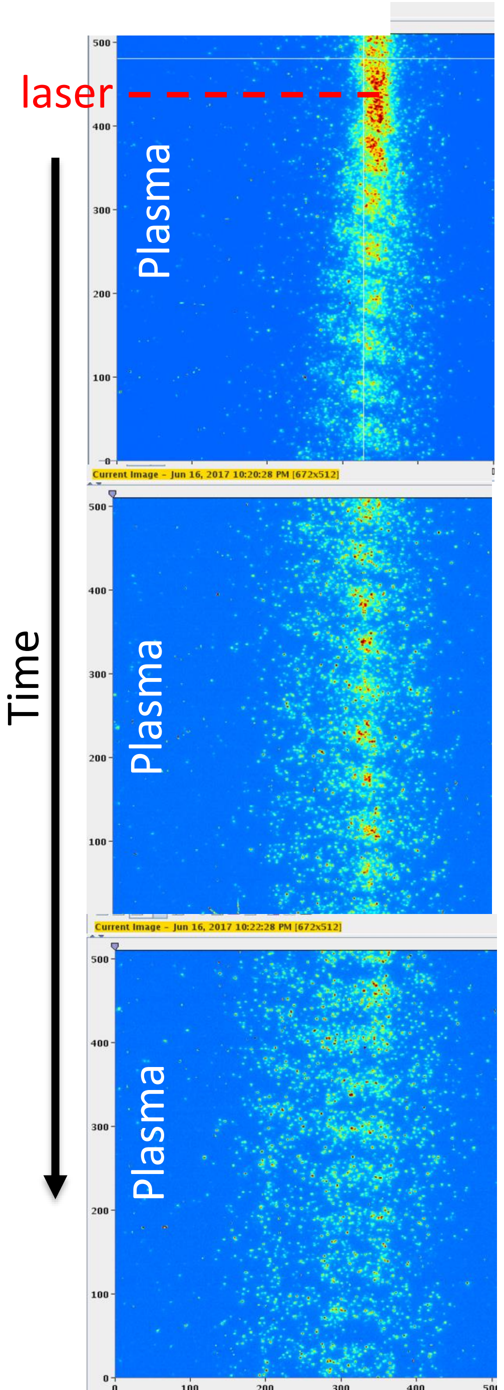
Observation of Seeded SMI

We scan the timing of the streak camera relative to the position of laser ionizations to attempt to observe the total number of microbunches in the beam.

Persistent microbunching is a good indication that the seeding is working and that a large amount of energy is transferred to the plasma wake.

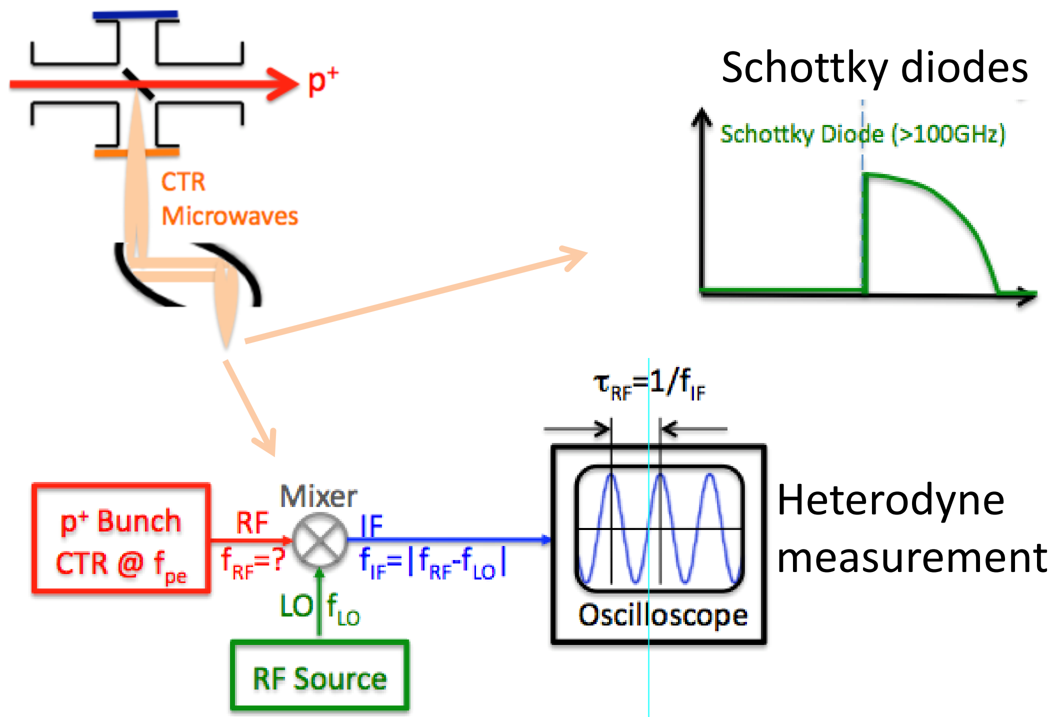
Preliminary!

K. Rieger, MPP



SMI measurements II: CTR

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



By mixing the CTR signal from the beam passage with a signal of known (similar) frequency, you can measure the resulting beatwave on a normal scope.

Excellent complement to the streak camera, which is resolution limited at the highest frequencies.

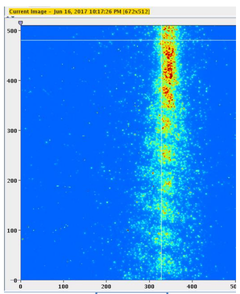
F. Braunmuller, M. Martyanov, MPP

Summary of OTR and CTR results

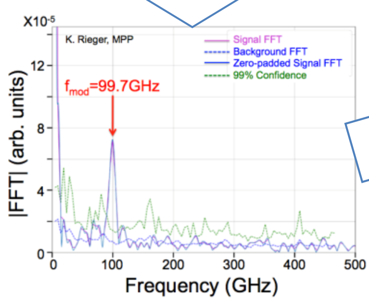
Preliminary!

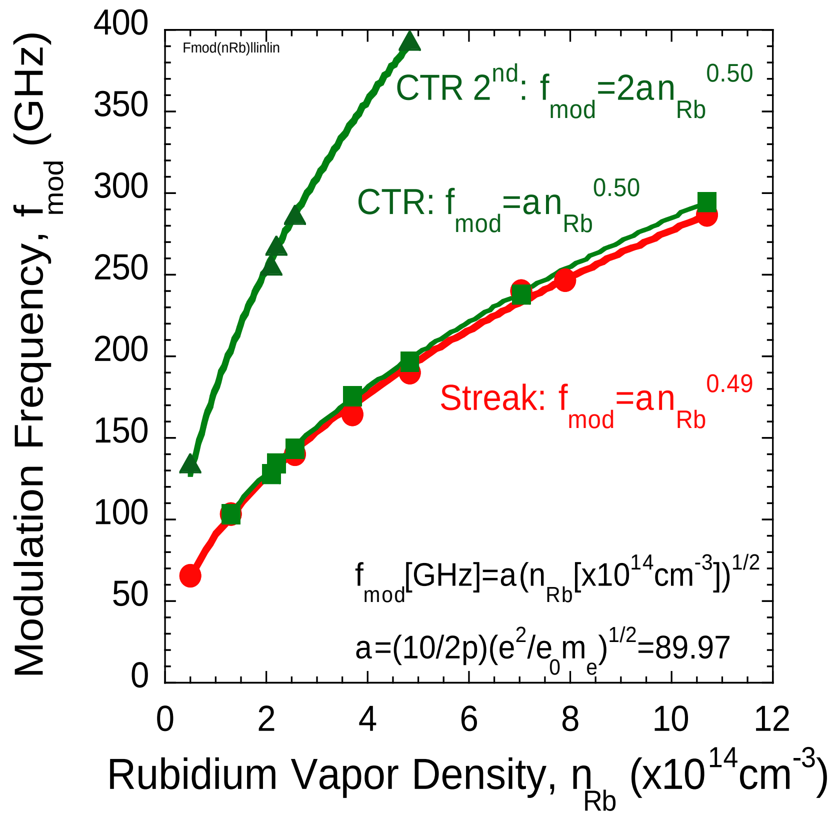
K. Rieger
M. Martyanov,
F. Braunmueller, MPP

OTR

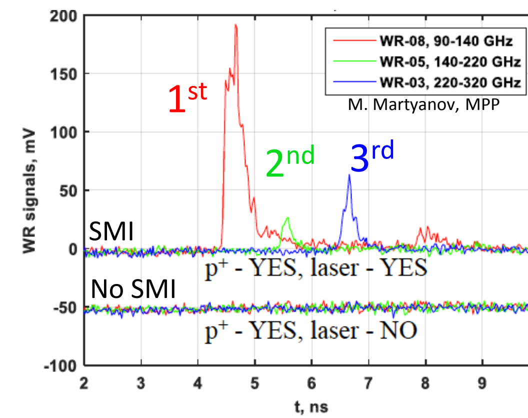


FFT



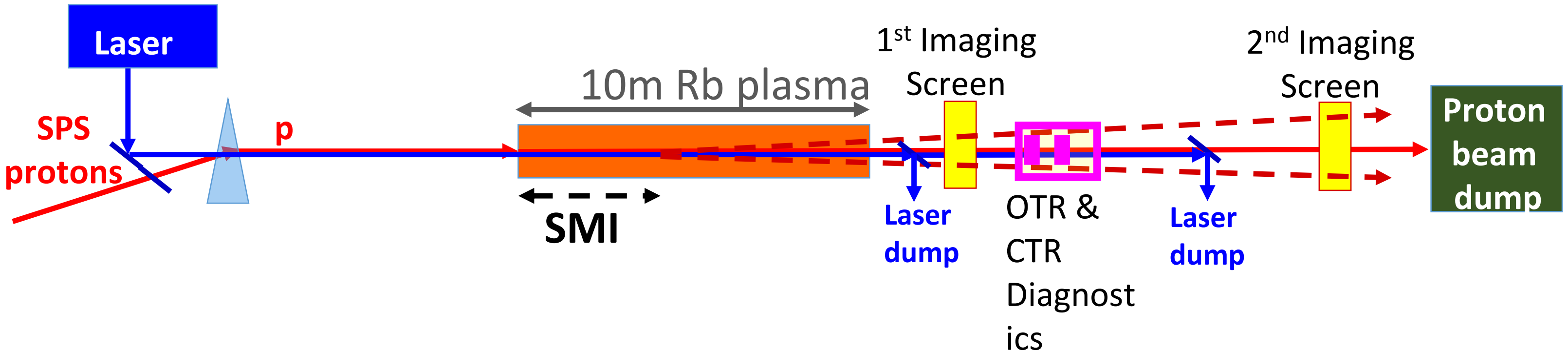


CTR



→ both OTR and CTR based measurements fit very well to predicted modulation frequency, for a range of plasma densities.

SMI measurements III: halo

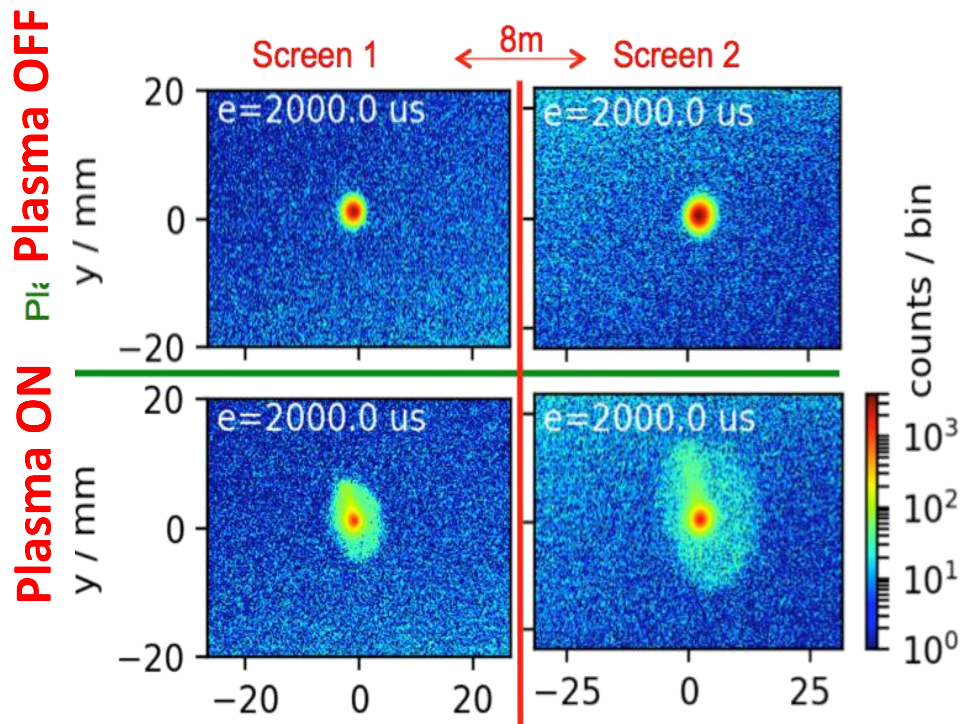


M. Turner, CERN

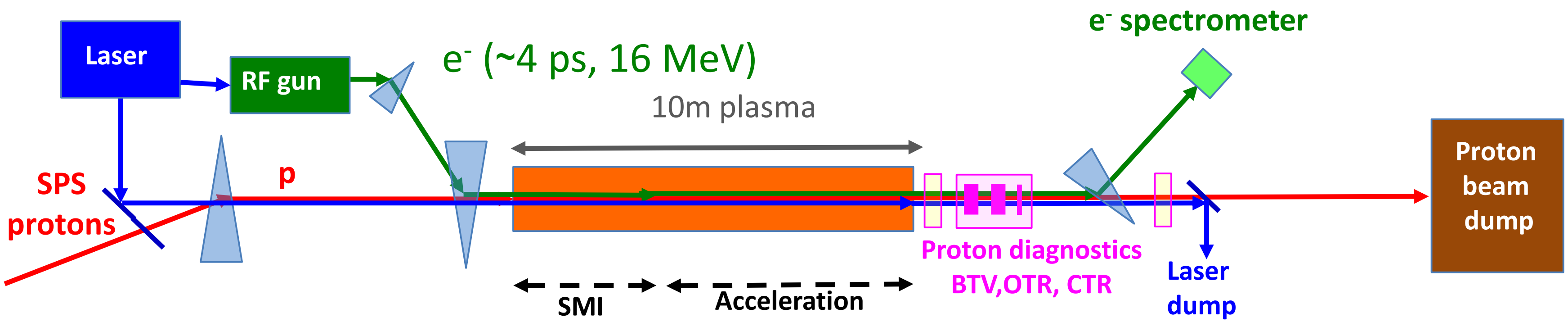
Indirect SSM Measurement: Image protons that got defocused by the strong plasma wakefields.

- → p^+ defocused by the transverse wakefield (SMI) form a halo
- → p^+ focused form a tighter core
- → Estimate of the transverse wakefields amplitude ($\int W_{per} dr$)
- → Additional evidence of instability

Preliminary!

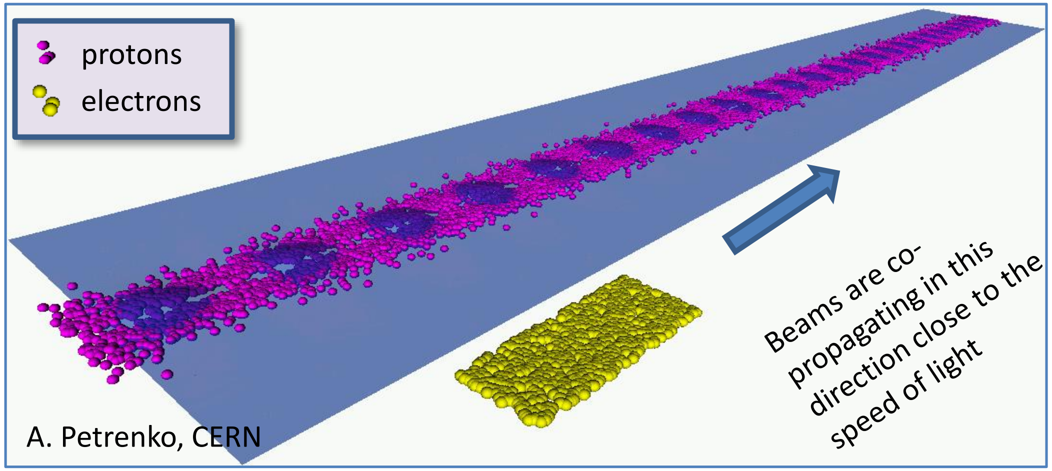


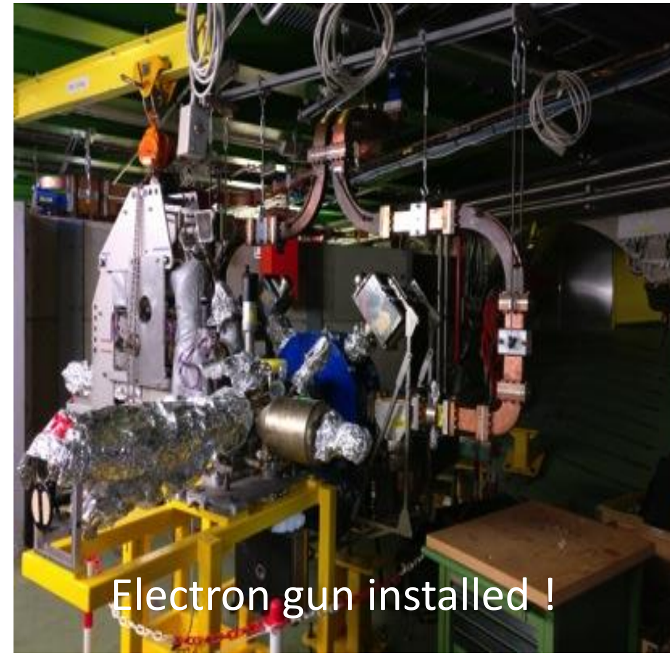
Phase 2: study wake structure with injected electrons



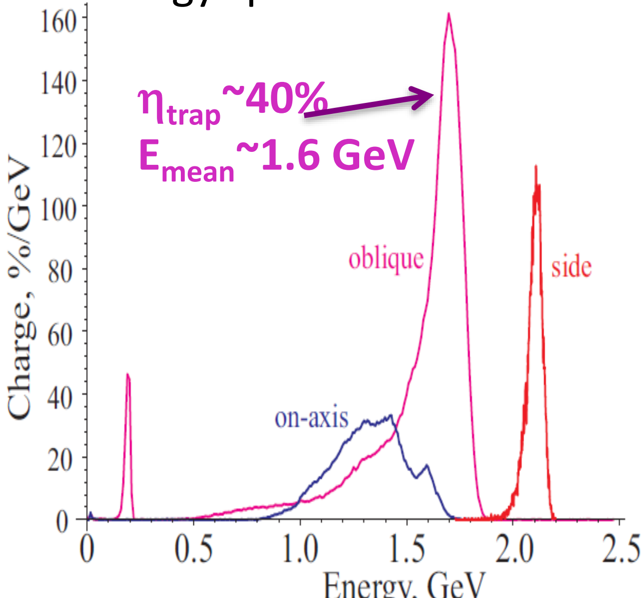
- **Goal**: probe the accelerating wakefields **with externally injected electrons**
  - **- Demonstrate GeV scale gradients** with proton driven wakefields
- Hardware commissioning end 2017
- First experimental runs in 2018

Electron Acceleration





Expected energy spectra :



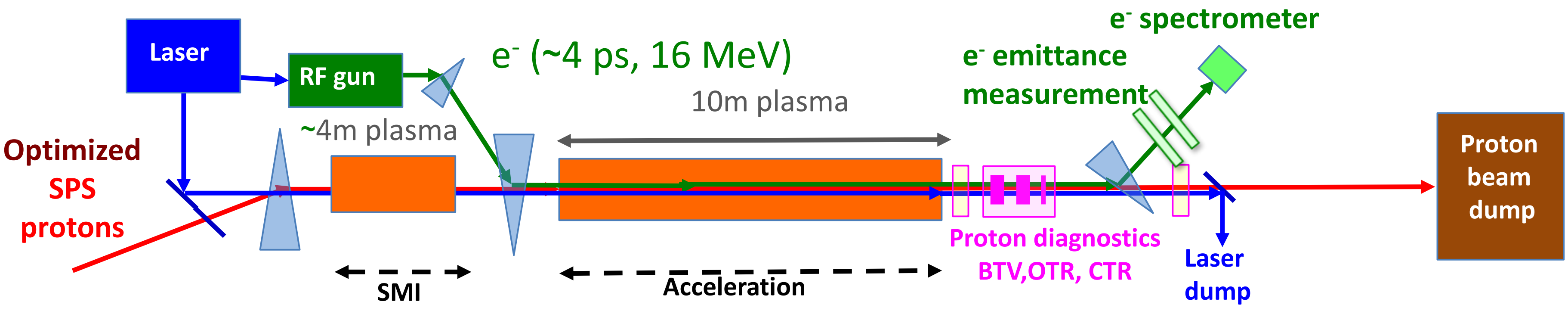
A. Caldwell et al., AWAKE Coll., Nucl. Instrum. A 829 (2016) 3

Bunch length~λ_p; sample all phases of wake field

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 energy spread.

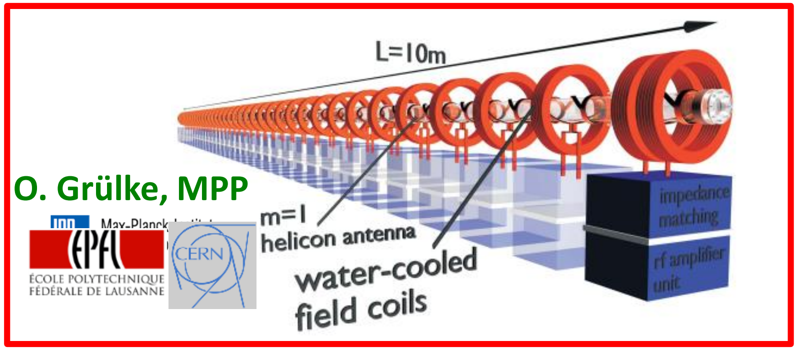
Run 2: accelerate a beam of electrons to several GeV



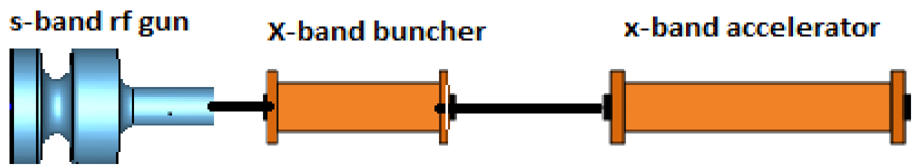
- **Goal 1: Accelerate a short electron beam**, while preserving beam quality as well as possible
- **Goal 2: Demonstrate scalability** of the AWAKE concept
  - sustain gradient in SMI wake over long distance
  - scalable length plasma sources
- **Start in 2021,** after the LHC Long Shutdown 2
- After the goals have been reached: target physics applications

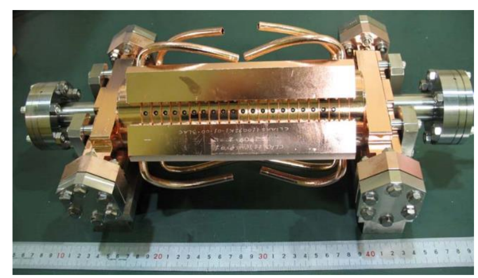
Run 2 studies on-going

Helicon plasma sources (scalable to 100s of meter)



New injectors (short bunch, high energy)

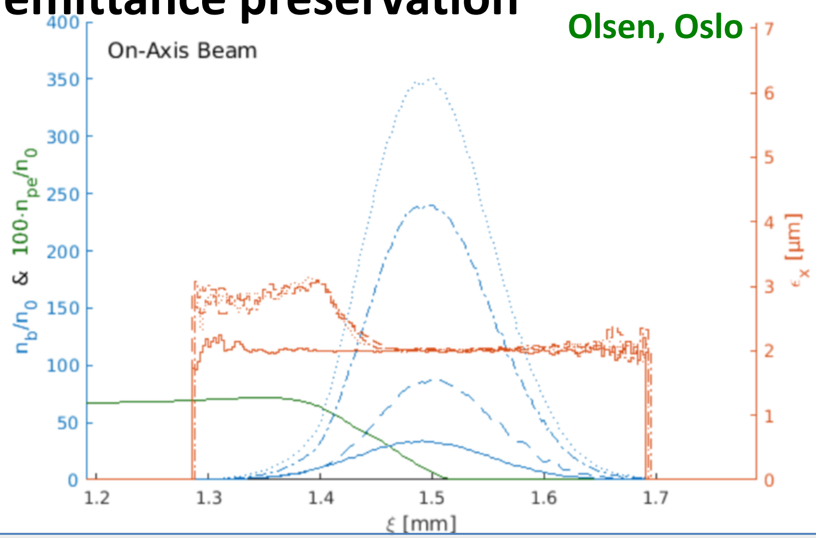




S. Doebert, CERN

Simulation studies of emittance preservation

V. Berglyd Olsen, Oslo



E.Adli, et al., "Towards AWAKE applications: Electron acceleration in a proton driven plasma wake", in Proc. IPAC'16, Busan, Korea, p. 2557

Particle Physics Perspectives

From Allen Caldwell

Started considering:

- **Physics with a high energy electron beam**
  - E.g., search for dark photons

- **Physics with an electron-proton or electron-ion collider**
  - Low luminosity version of LHeC
  - Very high energy electron-proton, electron-ion collider

Are there fundamental particle physics topics for high energy but low luminosity colliders ?

I believe – yes ! Particle physicists will be interested in going to much higher energies, even if the luminosity is low.

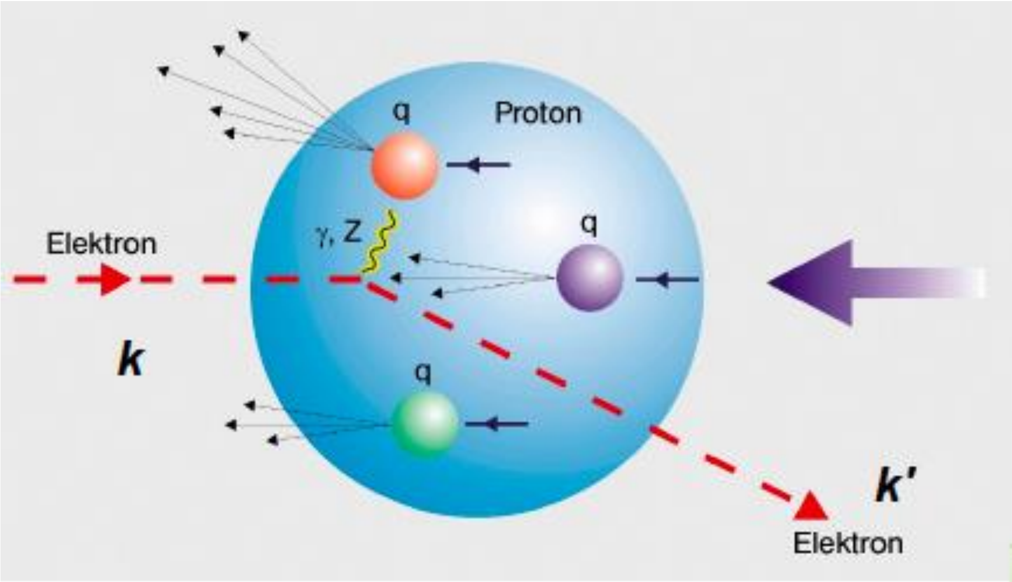
In general – start investigating the particle physics potential of an AWAKE-like acceleration scheme.

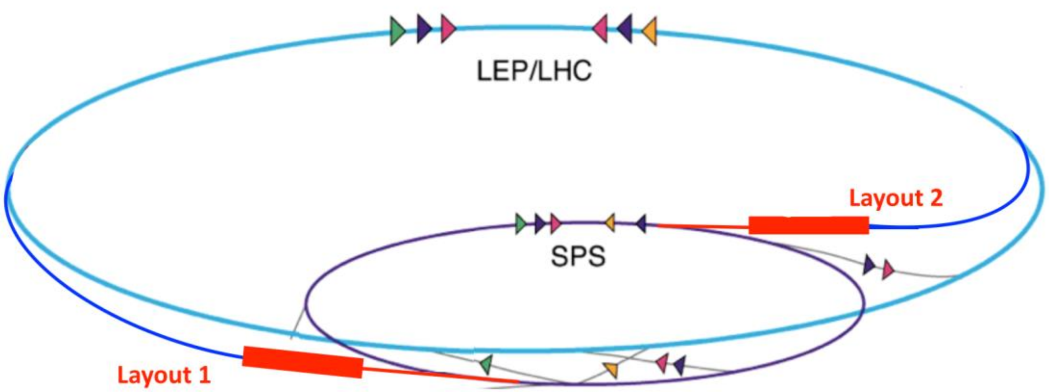
LHeC-like

From Allen Caldwell

Focus on QCD:

- Large cross sections – low luminosity (HERA level) enough
- Many open physics questions !
- Consider high energy **ep** collider with E_e up to O(50 GeV), colliding with LHC proton; e.g. Ee = 10 GeV, Ep = 7 TeV, √s = 530 GeV already **exceeds HERA cm energy**





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

Create ~50 GeV beam within 50−100 m of plasma driven by SPS protons and have an LHeC-type experiment.

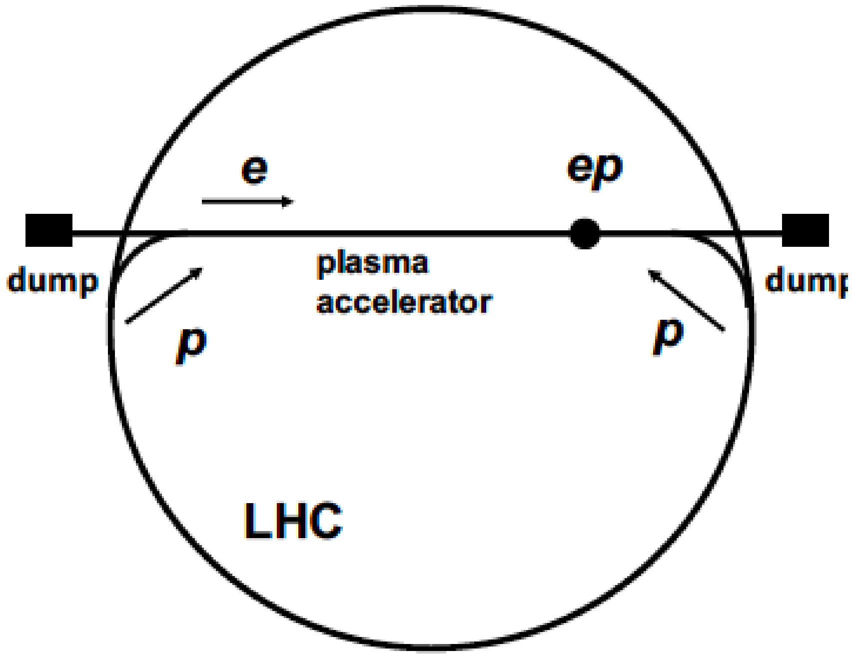
LHeC electron emittance requirements: ~50 um normalized emittance

Clear difference from LHeC is that luminosity currently expected to be $< 10^{30}$ cm^{-2} s^{-1}

VHEeP

From Allen Caldwell

(Very High Energy electron-Proton collider)



One proton beam used for electron acceleration to then collide with other proton beam

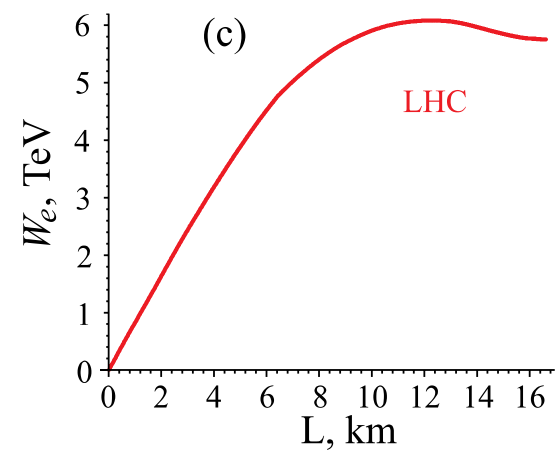
Luminosity ~ 10^{28} – 10^{29} cm^{-2} s^{-1} gives ~ 1 pb−1 per year.

Choose E_e = 3 TeV as a baseline for a new collider with 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

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

Electron energy from wakefield acceleration by LHC bunch

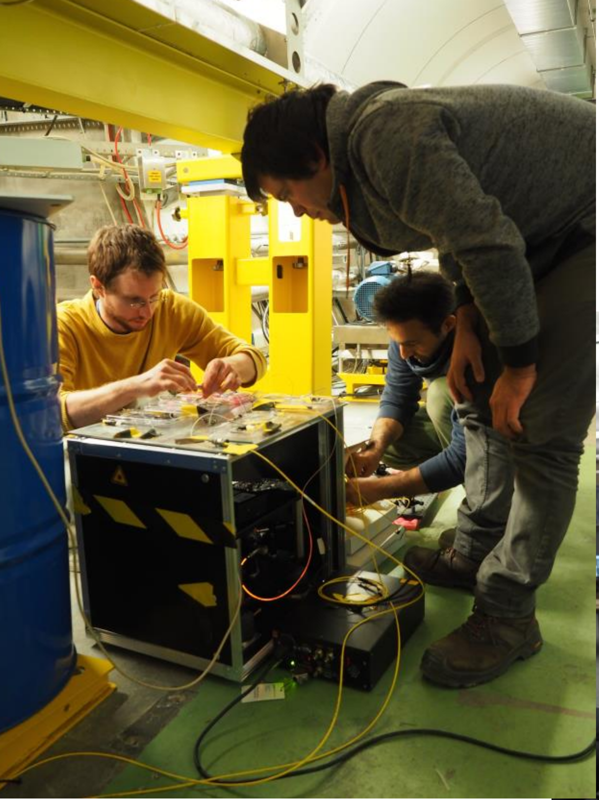


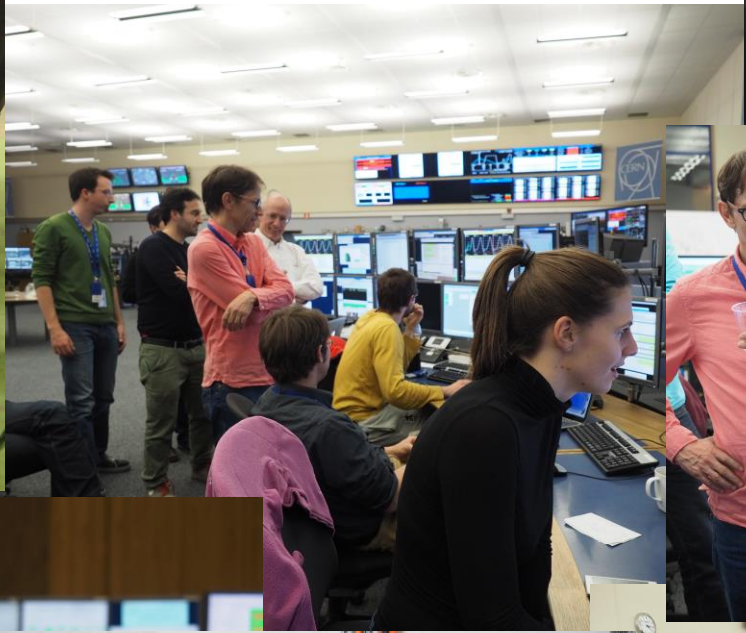
*A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)*

Conclusions

- Proton-driven PWA has the potential to accelerate electron beams to TeV in a single plasma stage
- The AWAKE experiment uses self-modulated SPS bunches as drivers
- First experiment goals reached: **SMI measured**
- Electron acceleration to be commissioned Q4/2017
- Planning for Run 2 (after 2020) and investigation of the physics potential well underway

Questions?



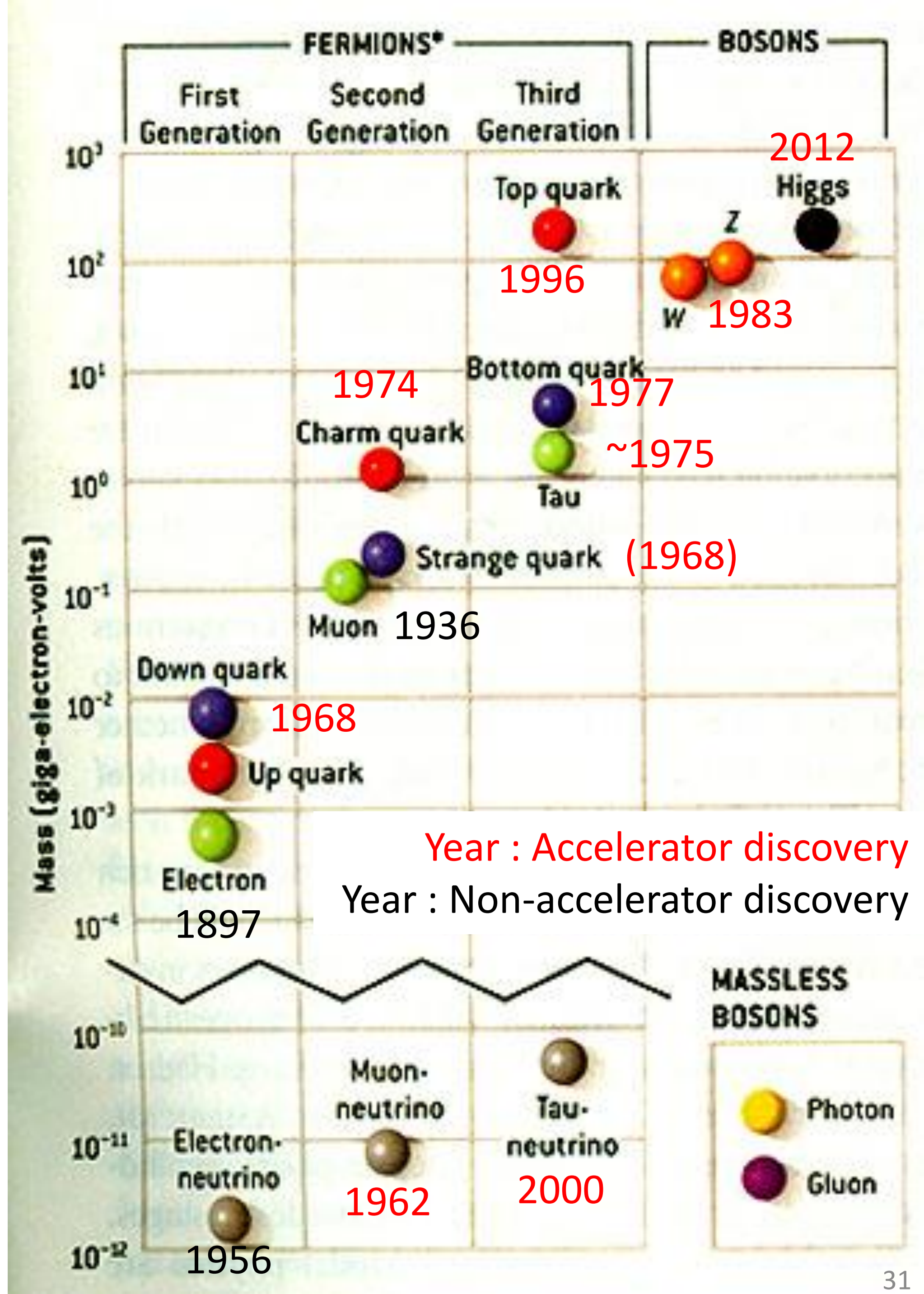


Extra

Particle accelerators

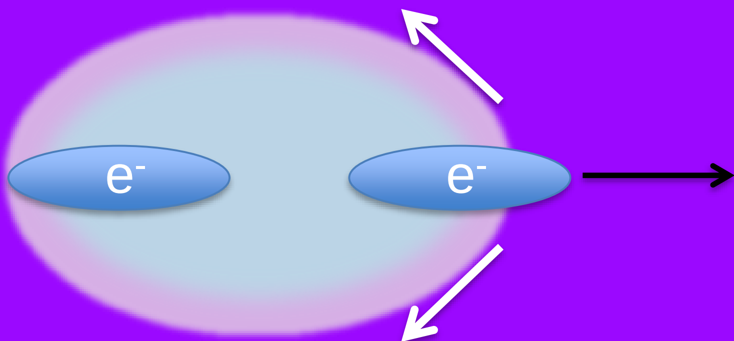
Most fundamental particles have been discovered by experiments using beams accelerated by a particle accelerator.

The discovery range has increased as particle accelerators have become more powerful.



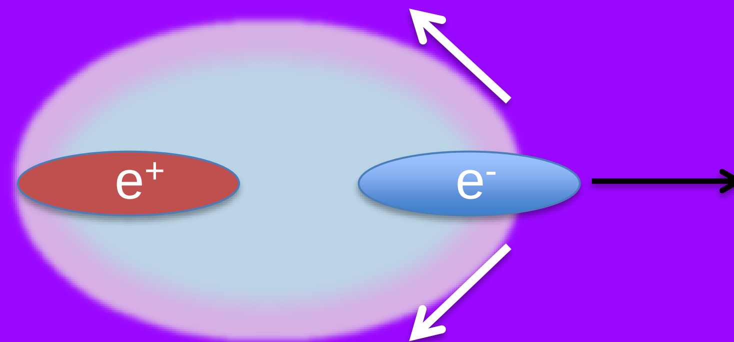
Driver-witness permutations

Electron driver, electron witness



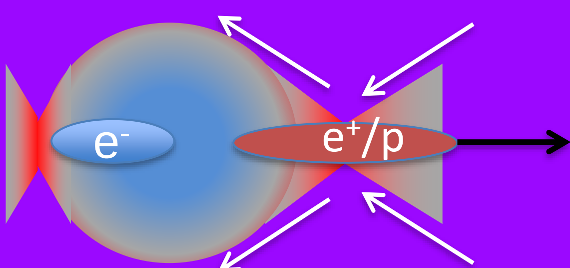
- Most studied case
- Potential applications: FEL, collider …

Electron driver, positron witness



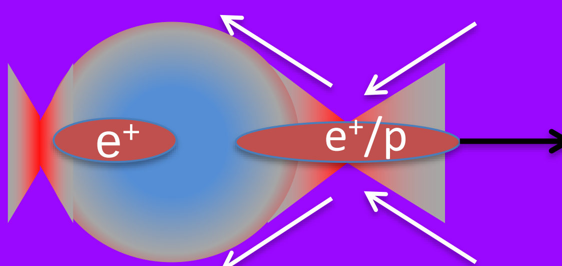
- Required for e- driven e- e+ collidier

Positron/proton driver, electron witness



- Potential applications : FEL, LC, LHeC …
- Studied at AWAKE

Positron/proton driver, positron witness

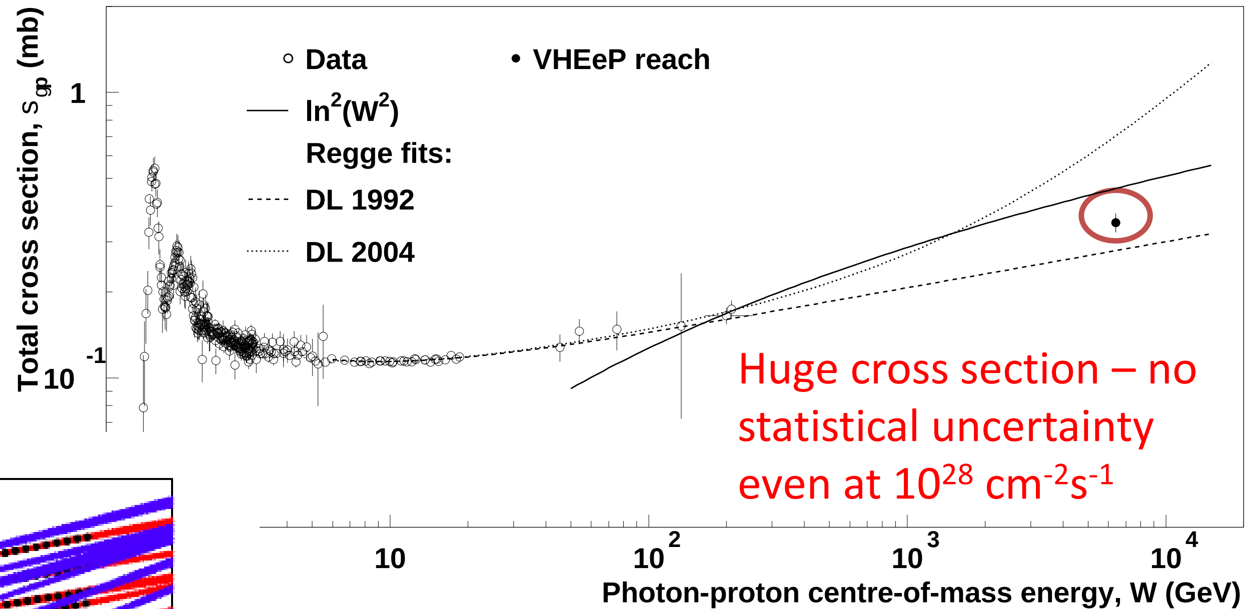


- Studied at FACET
- Interesting for LC afterburner

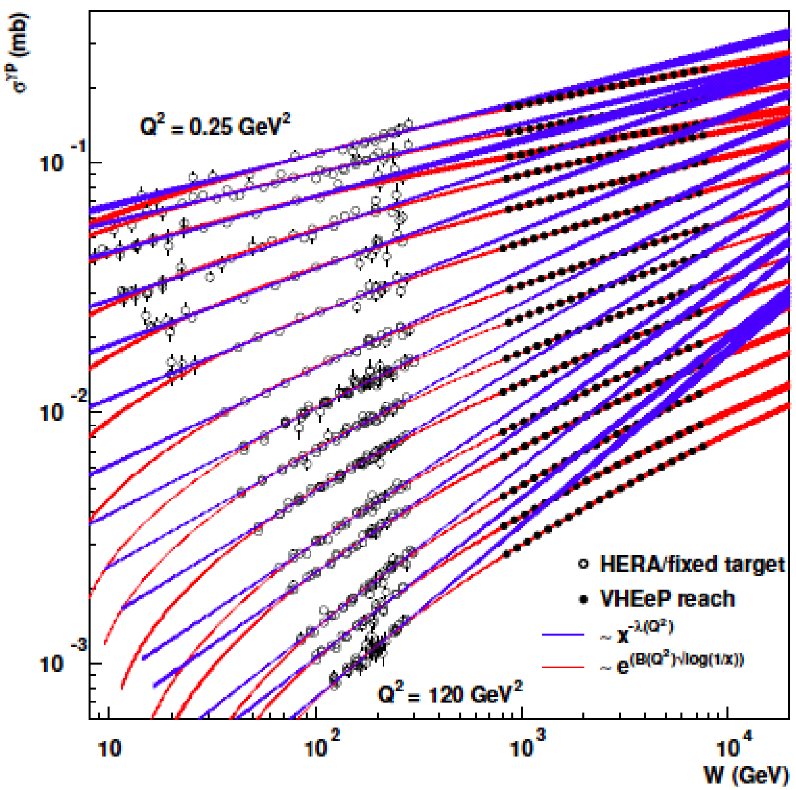
Physics Reach

From Allen Caldwell

Total photoproduction cross section – energy dependence ? Fundamental physics question, impact on cosmic ray physics



Huge cross section – no statistical uncertainty even at 10^{28} $cm^{-2}s^{-1}$



Virtual photon cross section – observation of saturation of parton densities ? Would provide information on the fundamental structure of the QCD vacuum.

+ BSM physics such as Leptoquarks, quark substructure, etc.