MAX-PLANCK-GESELLSCHAFT

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

1. Introduction to Proton-Driven PWA
2. AWAKE @ CERN
3. MPI specific activities

AWAKE

Allen Caldwell
Max-Planck-Institut für Physik

Proton-Driven Wakefield Acceleration

Both laser-driven and electron-bunch driven acceleration will require many stages to reach the TeV scale.

We know how to produce high energy protons (many TeV) in bunches with population > 10^{11}/bunch today, so if we can use protons to drive an electron bunch we could potentially have a simpler arrangement - single stage acceleration.

Linear regime ($n_b<n_0$):

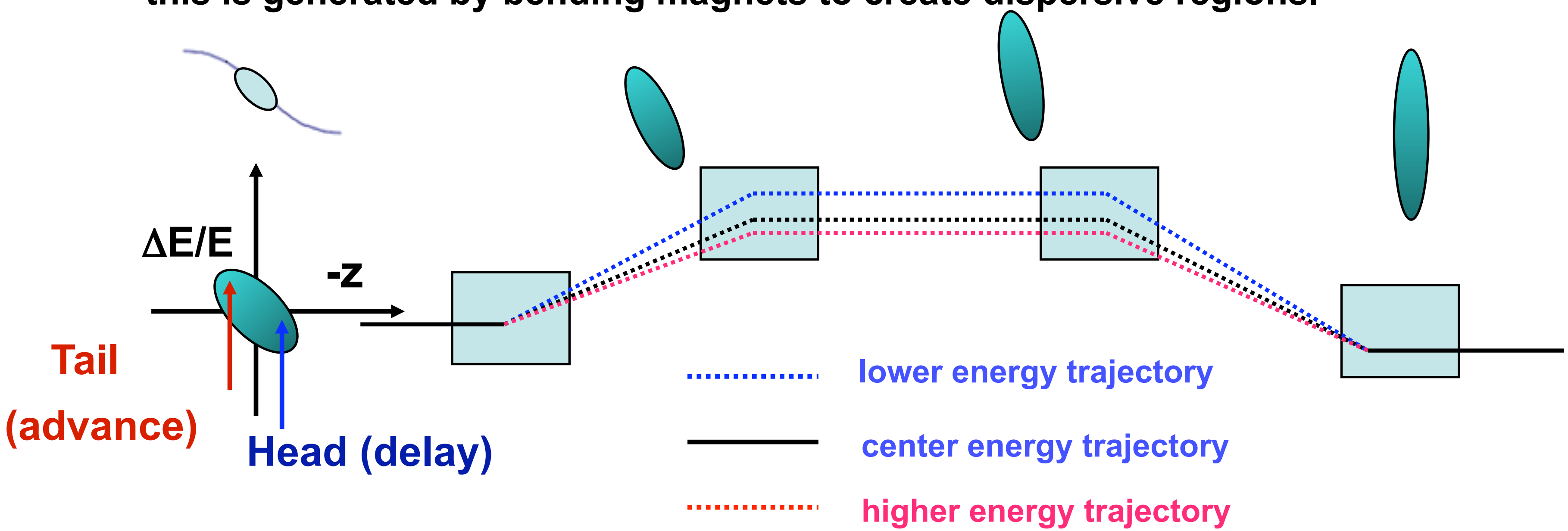
$$E_{z,\max} \approx 2\ \mathrm{GeV/m} \cdot \left(\frac{N_b}{10^{10}}\right) \cdot \left(\frac{100\ \mu\mathrm{m}}{\sigma_z}\right)^2$$

Need very short proton bunches for strong gradients. Today's proton beams have

$$\sigma_z \approx 10 - 30\ \mathrm{cm}$$

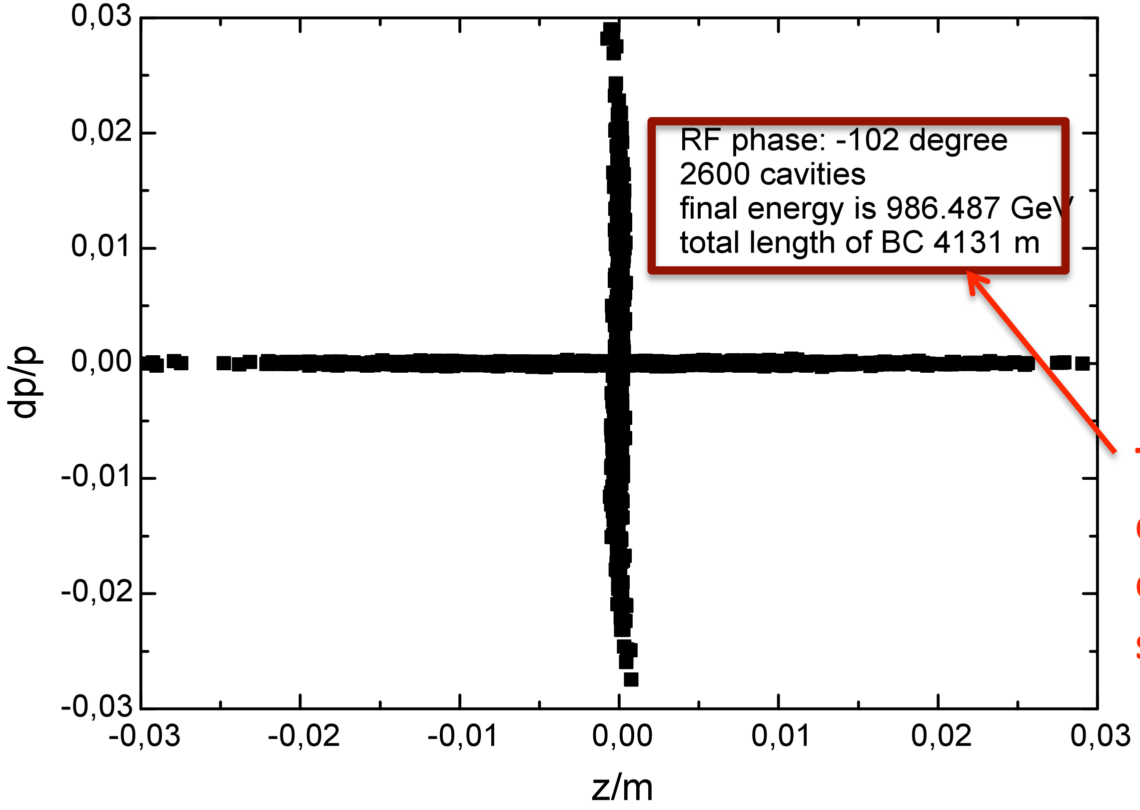
Magnetic bunch compression (BC)

- **Beam compression can be achieved:**
  (1) by introducing an energy-position correlation along the bunch with an RF section at zero-crossing of voltage
  (2) and passing beam through a region where path length is energy dependent: this is generated by bending magnets to create dispersive regions.



- **To compress a bunch longitudinally, trajectory in dispersive region must be shorter for tail of the bunch than it is for the head.**

Phase space of beam

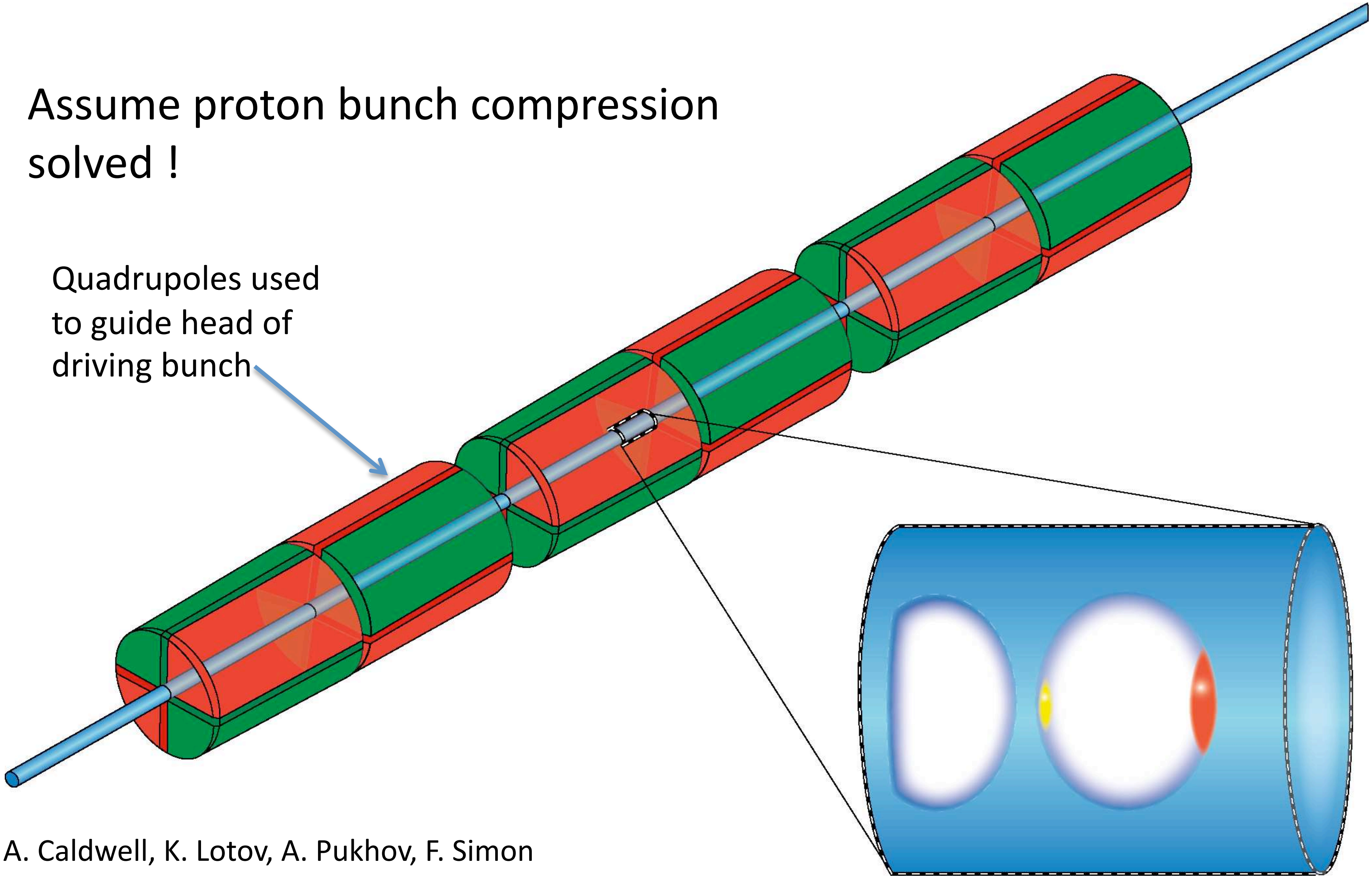


Too long – use in combination with other compression schemes

See A. Caldwell, G. Xia et al., Preliminary study of proton driven plasma wakefield acceleration, Proceedings of PAC09, May 3-8, 2009, Vancouver, Canada

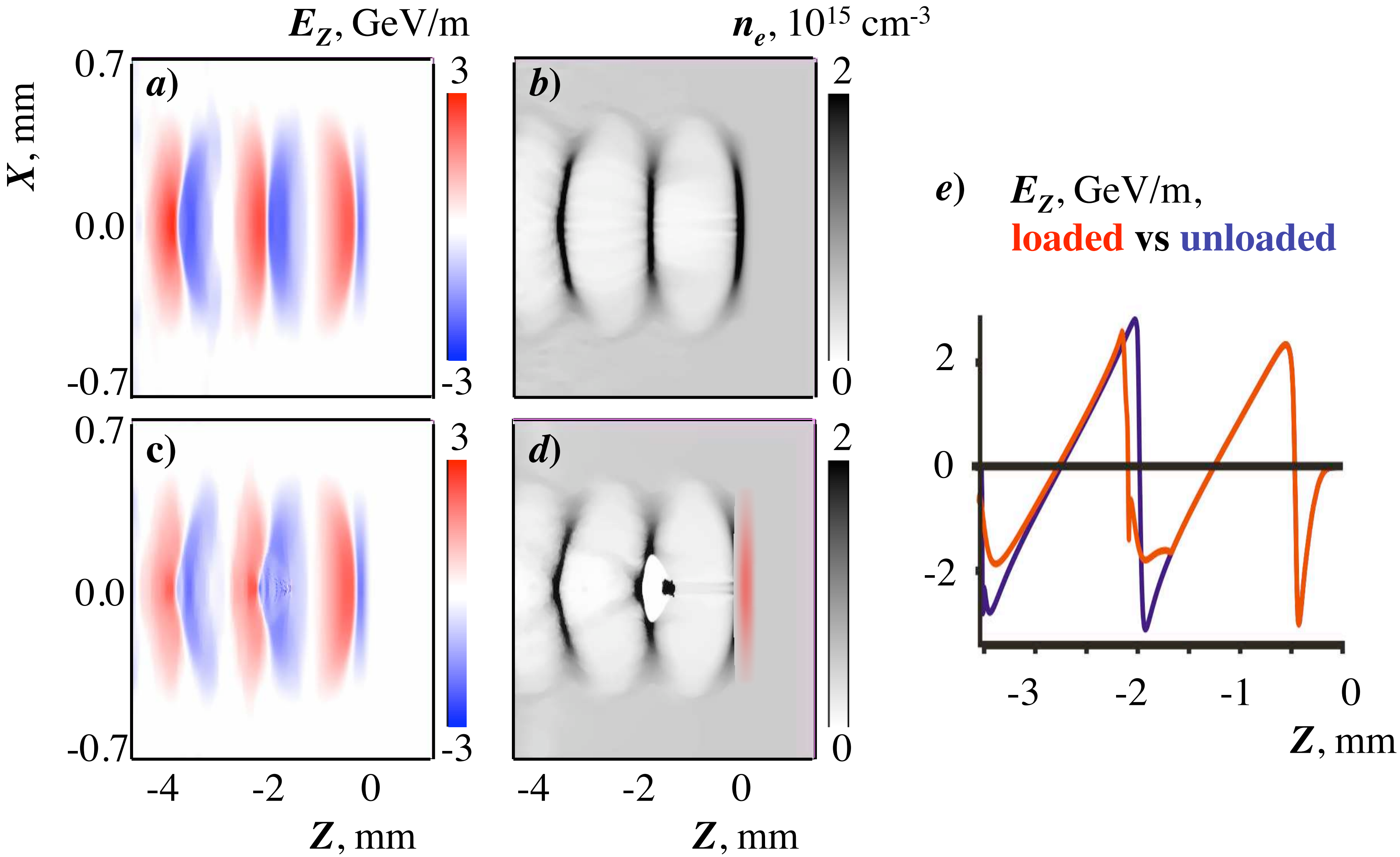
Simulation study

Assume proton bunch compression solved !



A. Caldwell, K. Lotov, A. Pukhov, F. Simon
Nature Physics ***5, 363 - 367 (2009)***

Densities & Fields



PWA via Modulated Proton Beam

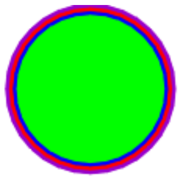
Producing short proton bunches not possible today w/o major investment. Not an option for the short term …

Instead, we investigated modulating a long bunch to produce a series of 'micro'-bunches in a plasma.

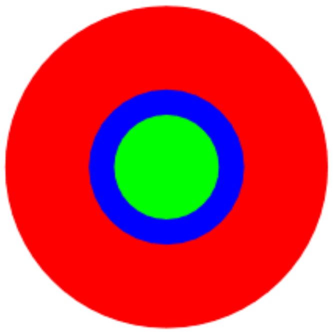
The microbunches are generated by a transverse modulation of the bunch density (transverse two-stream instability). The microbunches are naturally spaced at the plasma wavelength, and act constructively to generate a strong plasma wake. Investigated both numerically and theoretically (N. Kumar, A. Pukhov, and K. V. Lotov, Phys. Rev. Lett. **104**, 255003 (2010)).

Seeding the correct instability

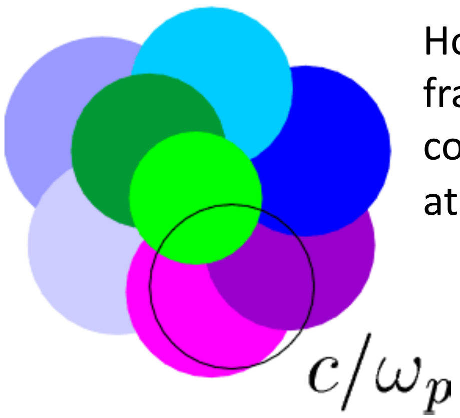
Spontaneous instability vs Seeded instability



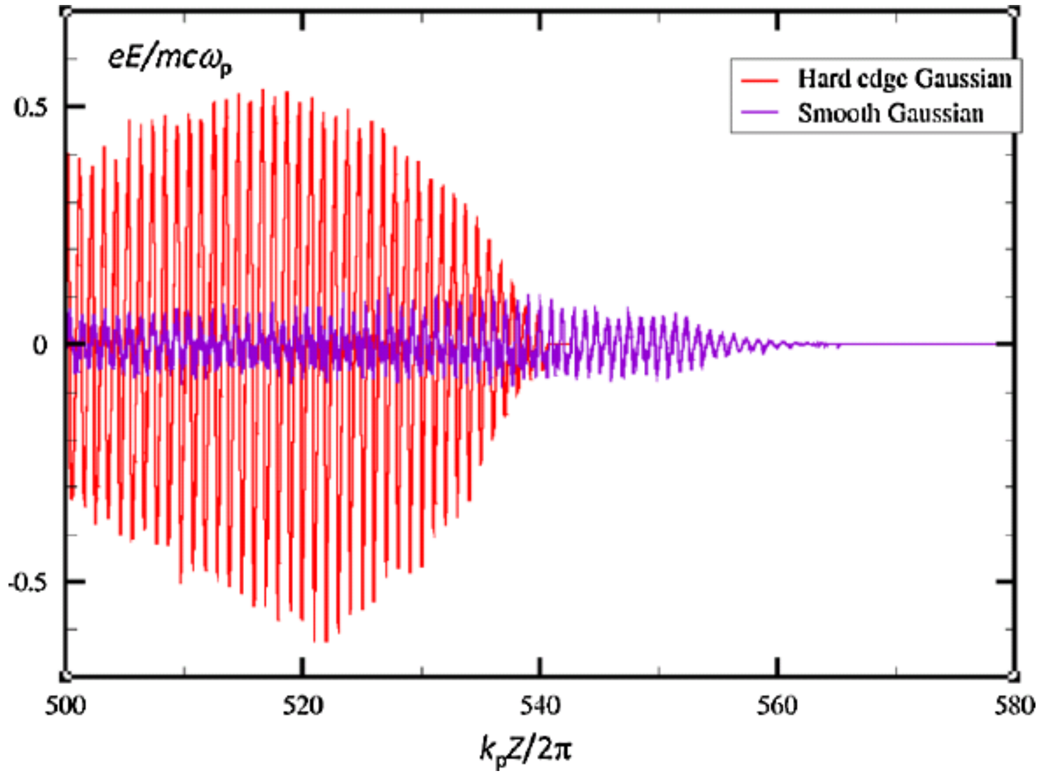
Original beam
(front view)



Axisymmetric mode (half of the beam contributes to on-axis field excitation)



Hosing mode (small fraction of the beam contributes to the field at a given point)



Need to avoid hosing to produce strong fields

Instability seeding is necessary to produce the axially symmetric mode

Phase velocity of the wake

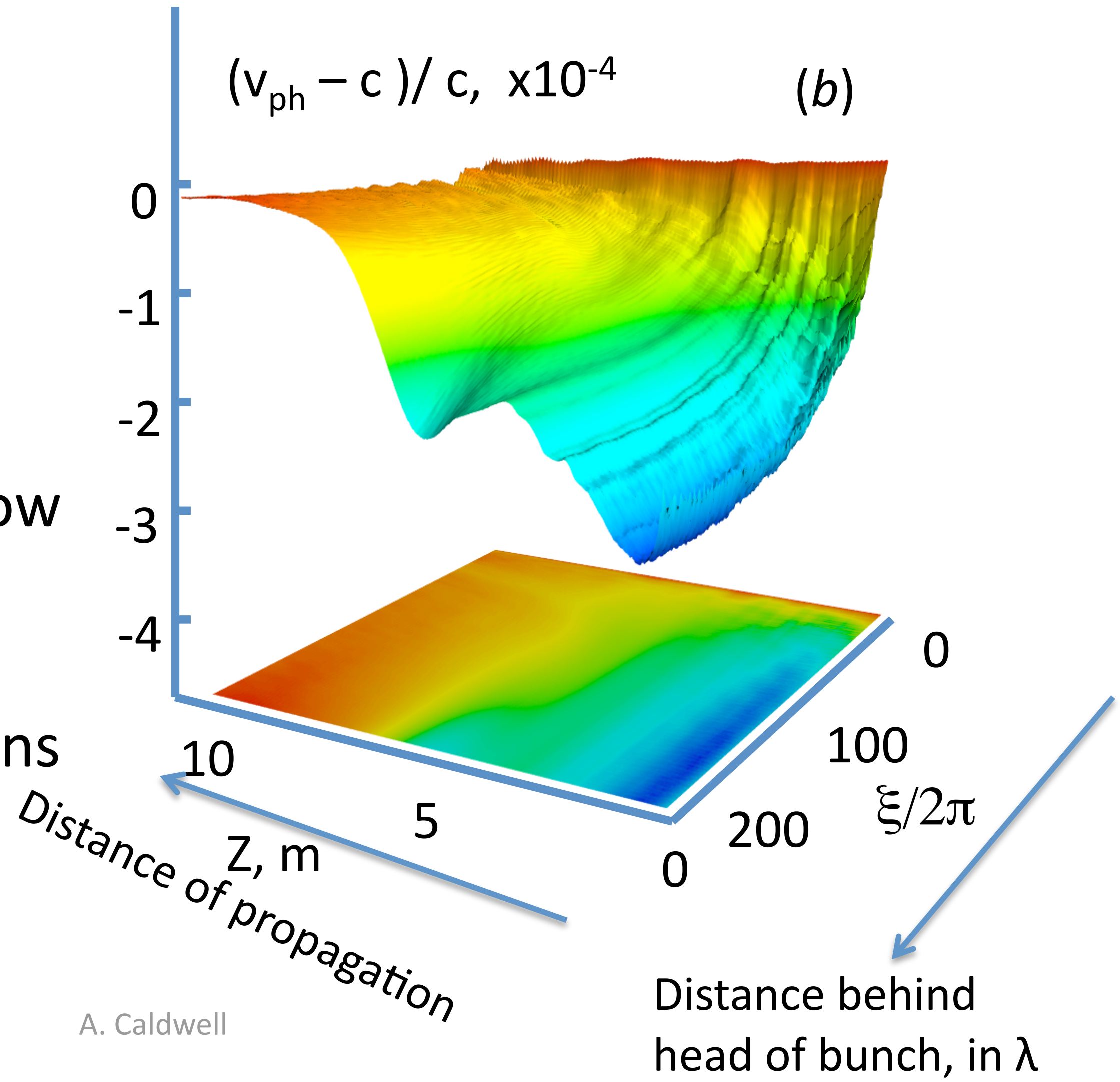
To trap & accelerate electrons in the wake of the protons, it is important that the wake phase velocity matches the electron velocity. Initially, the gamma-factor is

γ_{min}~ 40

This is order of magnitude below that of the beam.

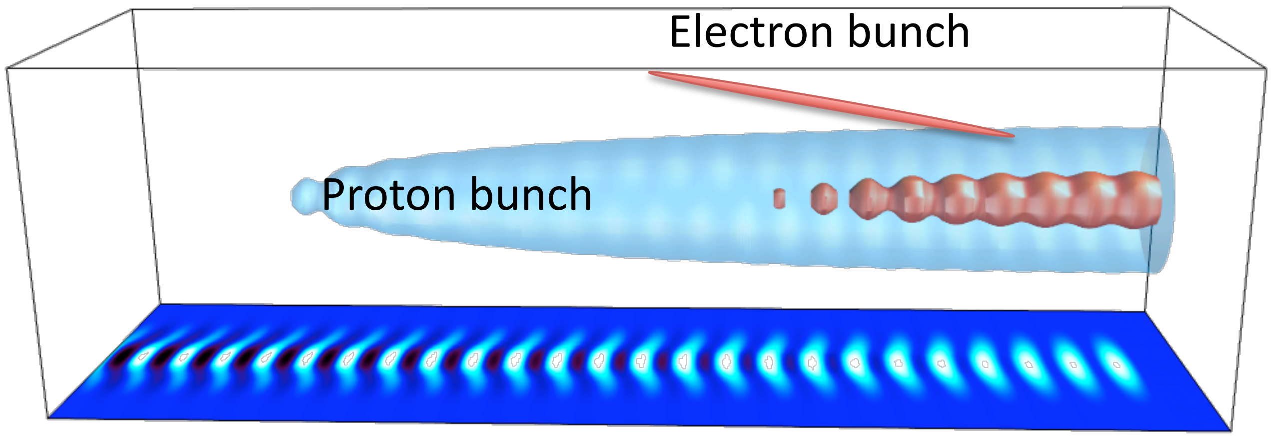
Requires that we inject electrons after the phase velocity has stabilized.

Pukhov et al., Phys Rev Lett (2011)



Solution: Delayed Electron Injection

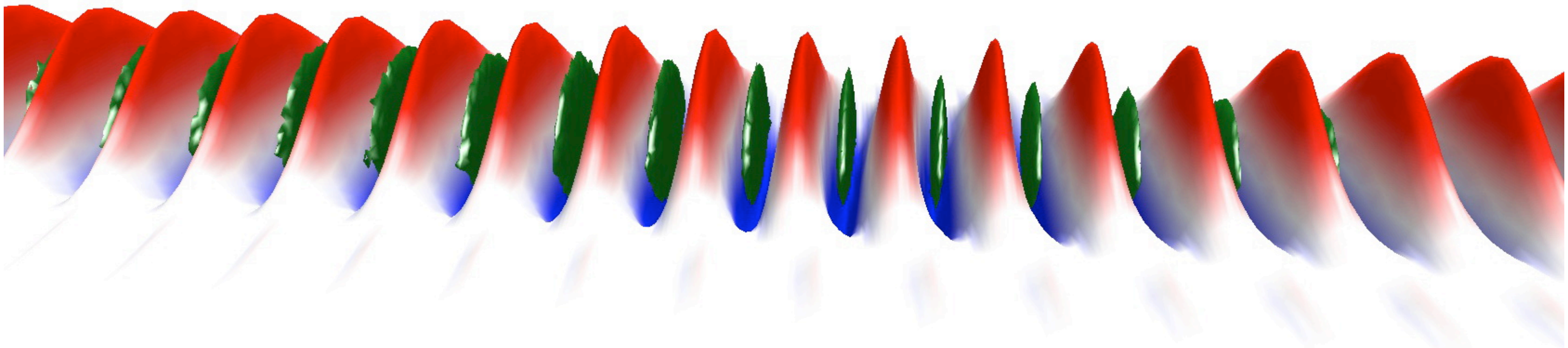
Single plasma cell case:



Electron bunch injected off-axis at an angle, so that it merges with the proton bunch once the modulation is developed and the phase velocity is high.

Electron injection

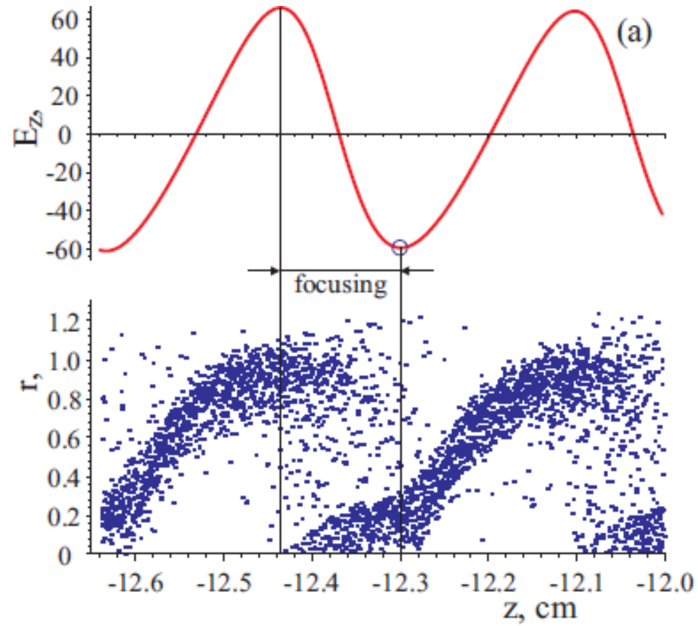
Side injection after 6 meters, at 0.005 rad angle, 8 MeV electrons



Side injection: high efficiency trapping of electrons, small energy spread

K. Lotov

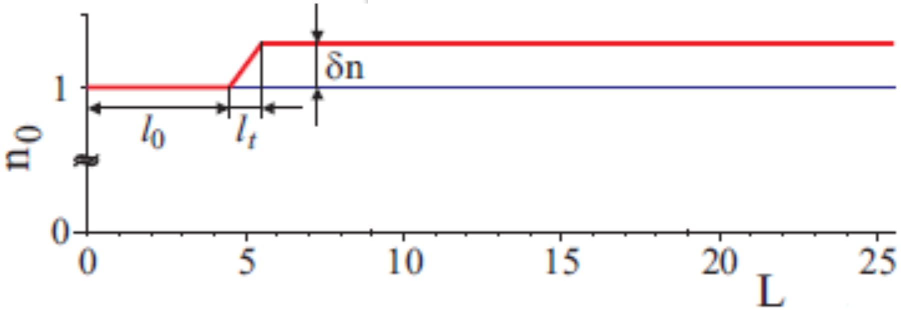
Perspectives: eventually, we want 100's of GeV, but ...



... wakefield amplitude quickly drops after the beam gets modulated.

Reason: defocusing regions keep on moving along the beam and destroys the bunches.

Remedy: control of the wave phase by the plasma density profile



We will need precise control of plasma density ! Also needed for successful electron acceleration. Goal is 0.1-0.5% (still being defined).

Date: May 31, 2011

Proto-collaboration with 25 institutes, including world-experts in all needed categories

Letter of Intent for a Demonstration Experiment in Proton-Driven Plasma Wakefield Acceleration

E. Adli[24], W. An[22], R. Assmann[3], R. Bingham[19], A. Caldwell[16], S. Chattopadhyay[4], N. Delerue[12], F. M. Dias[8], I. Efthymiopoulos[3], E. Elsen[5], S. Fartoukh[3], C. M. Ferreira[8], R. A. Fonseca[8], G. Geschonke[3], B. Goddard[3], O. Grülke[17], C. Hessler[3], S. Hillenbrand[11], J. Holloway[19,23], C. Huang[14], D. Jarozinsky[25], S. Jolly[23], C. Joshi[22], N. Kumar[7], W. Lu[21,22], N. Lopes[8], M. Kaur[18], K. Lotov[2], V. Malka[13], M. Meddahi[3], O. Mete[3], W.B. Mori[22], A. Mueller[11], P. Muggli[16], Z. Najmudin[9], P. Norreys[19], J. Osterhoff[5], J. Pozimski[9], A. Pukhov[7], O. Reimann[16], S. Roesler[3], H. Ruhl[15], H. Schlarb[5], B. Schmidt[5], H.V.D. Schmitt[16], A. Schöning[6], A. Seryi[10], F. Simon[16], L.O. Silva[8], T. Tajima[15], R. Trines[19], T. Tückmantel[7], A. Upadhyay[7], J. Vieira[8], O. Willi[7], M. Wing[23], G. Xia[16], V. Yakimenko[1], X. Yan[20], F. Zimmermann[3]

Interesting mix of theorists & experimentalists

Particle physicists, accelerator physicists, plasma physicists

1 Brookhaven National Laboratory, Brookhaven, USA
2 Budker Institute of Nuclear Physics, Novosibirk, Russia
3 CERN, Geneva, Switzerland
4 Cockroft Institute, Daresbury, UK
5 DESY, Hamburg, Germany
6 Universität Heidelberg, Heidelberg, Germany
7 Heinrich Heine University, Düsseldorf, Germany
8 Instituto de Plasmas e Fusao Nuclear, IST, Lisboa, Portugal
9 Imperial College, London, UK
10 John Adams Institute for Accelerator Science, Oxford, UK
11 Karlsruher Institute of Technology KIT, Karlsruhe, Germany
12 LAL, Univ Paris-Sud, CNRS/IN2P3, Orsay, France
13 LOA, Laboratoire dOptique Applique, CNRS/ENSTA/X, France
14 Los Alamos National Laboratory, NM, USA
15 Ludwig Maximilian University, Munich, Germany
16 Max Planck Institute for Physics, Munich, Germany
17 Max Planck Institute for Plasma Physics, Greifswald, Germany
18 Panjab University, Chandigarh, India
19 Rutherford Appleton Laboratory, Chilton, UK
20 State Key Laboratory of Nuclear Physics and Technology, Peking University, China
21 Tsinghua University, Beijing, China
22 University of California, Los Angeles, CA, USA
23 University College London, London, UK
24 University of Oslo, Oslo, Norway
25 University of Strathclyde, Glasgow, Scotland, UK

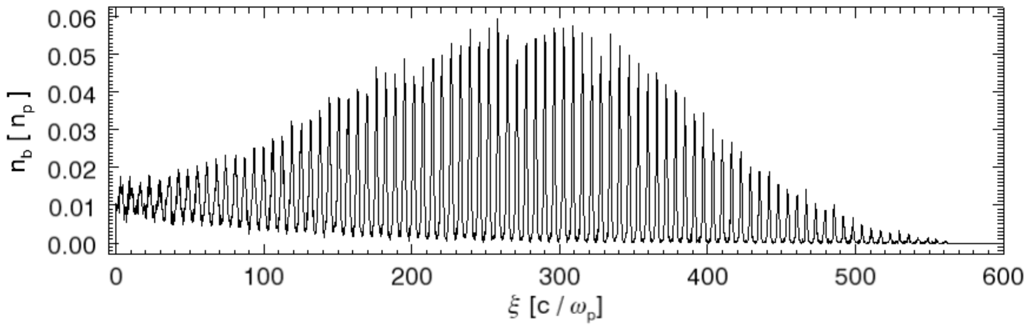
Positive review by SPSC October 2011

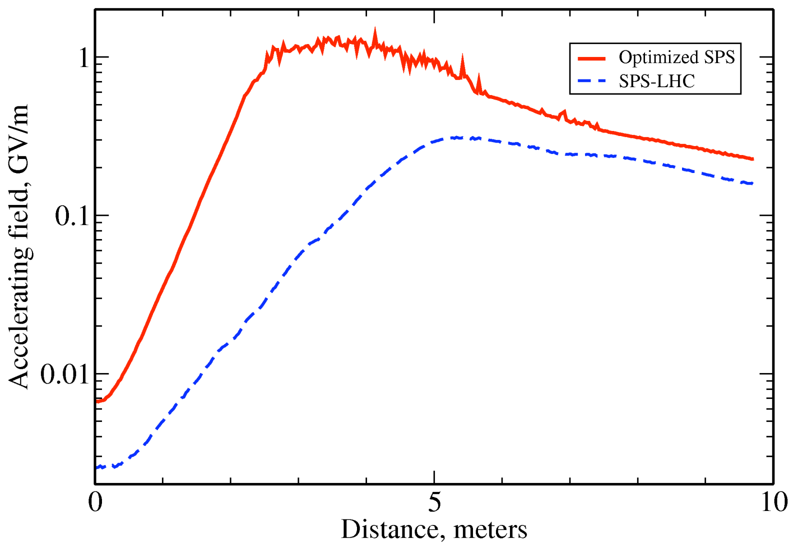
Project Structure

- **AWAKE Collaboration**
  Spokesperson: Allen Caldwell
  Deputy: Matthew Wing
  - **Experiment Coordinator**
    Patric Muggli
    - **Metal Vapor Plasma Cell WP** – Erdem Öz
    - **Helicon Plasma Cell WP** – Olaf Grülke
    - **Pulsed Discharge Plasma Cell WP** – Nelson Lopes
    - **Electron Spectrometer WP** – Simon Jolly
    - **Optical Diagnostics WP** – TBD
    - **Electron Source WP** – Tim Noakes
  - **Simulation/Theory Coordinator**
    Konstantin Lotov
    - **Simulations WP** – Konstantin Lotov
  - **Accelerator & Infrastructure Coordinator**
    Edda Gschwendtner (CERN Project leader)
    - **Project Management WP** – Edda Gschwendtner
    - **RP and Safety WP** – Helmut Vincke
    - **Experimental Area WP** – Edda Gschwendtner
      - **Interface p/e/laser/plasma WP** – Edda Gschwendtner
      - **Layout, Integration Coordination WP** – Ans Pardons
      - **Secondary Beam Diagnostics WP** – TBD
      - **General Services WP** – TBD
    - **SPS Beam WP** – TBD
    - **Beam-Line WP** – Chiara Bracco
      - **Proton Beam-Line WP** – Chiara Bracco
      - **Electron Beam-Line WP** – Chiara Bracco

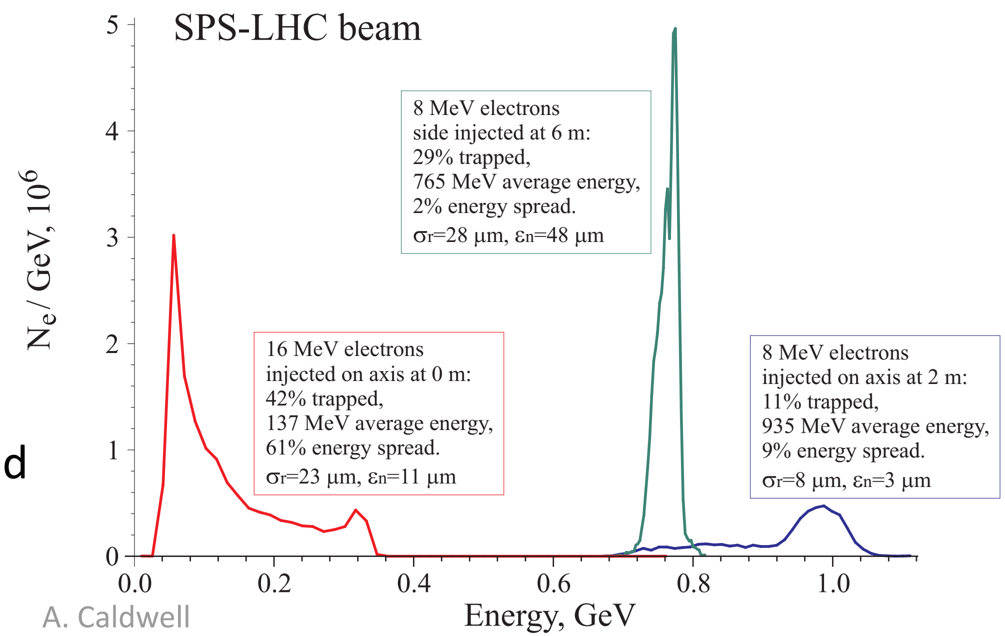
Expected Results

A long SPS drive beam will be sent into a 5-10m long plasma cell. A self-modulation of the beam due to the transverse wakefield occurs which produces many ultrashort beam slices.



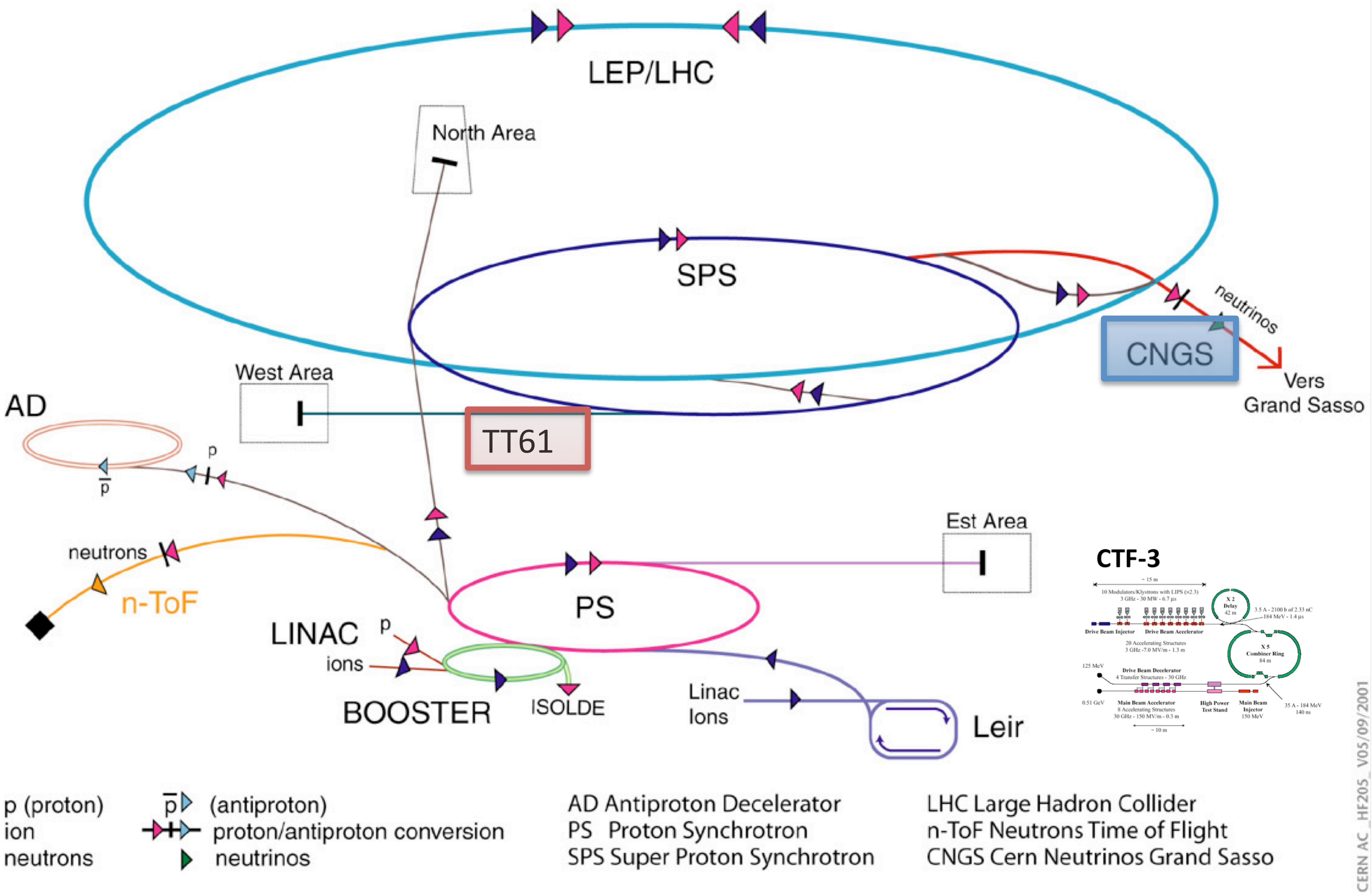


The modulation resonantly drives wakefields in the 100-1000 MV/m regime.



Particle-in-cell simulations predict acceleration of injected electrons to beyond 1 GeV.

Accelerator chain of CERN (operating or approved projects)



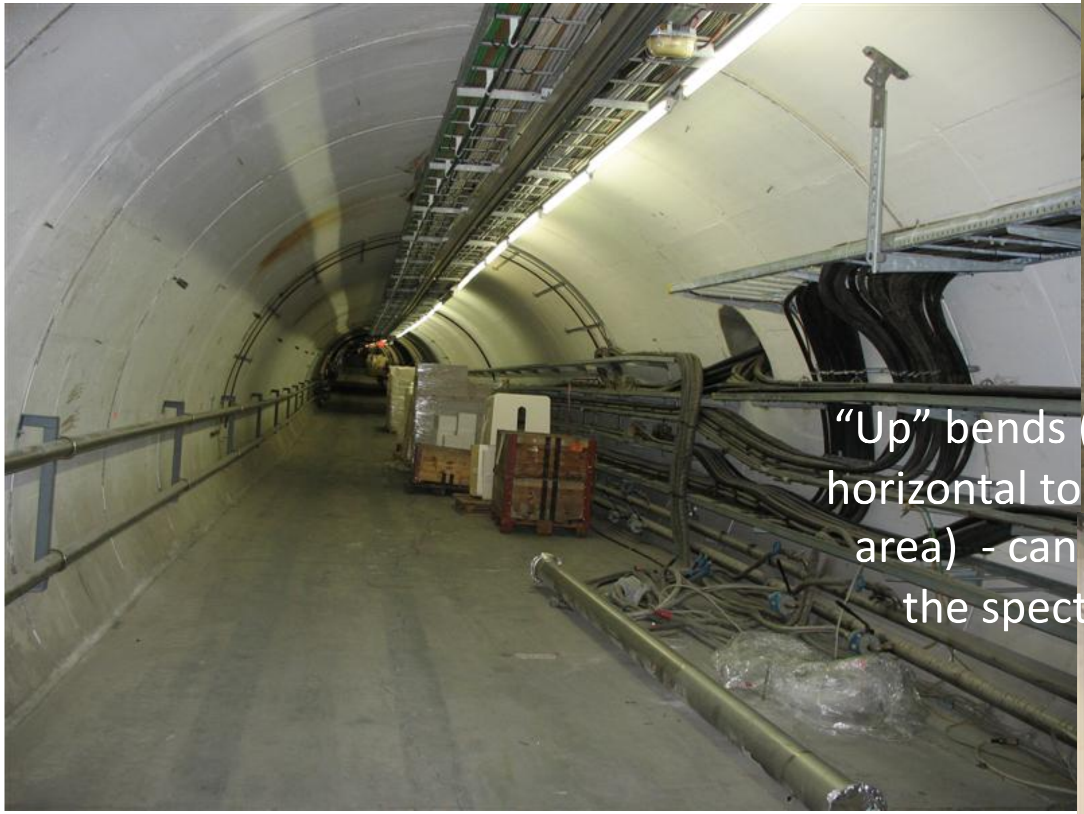
p (proton)
ion
neutrons

p̄ (antiproton)
proton/antiproton conversion
neutrinos

AD Antiproton Decelerator
PS Proton Synchrotron
SPS Super Proton Synchrotron

LHC Large Hadron Collider
n-ToF Neutrons Time of Flight
CNGS Cern Neutrinos Grand Sasso

TT61 tunnel today



"Up" bends (bring beam horizontal to the old exp. area) - can be used as the spectrometer

End tunnel to be converted to **beam dump**

Milestones

March 2012 (Conceptual Design Report) (delayed to March 2013)
Demonstrate at least one technology for a 1m long plasma cell with 10^{14} cm^{-3} density, uniformity better than 5% (unlikely in 2012)

Define seeding scenario in 3D simulations, define experimental test

Technical design of electron beam injection into plasma + spectrometer + dump + proton beam line. (on track)

Radiation and safety study. (on track)

Layout of experimental area (p delivery&dump, e injector+spectrometer +dump, plasma cell, diagnostics, lasers) (on track)

Milestones-Continued

Dec 2013

Demonstrate at least one technology for a plasma length 5m with 10^{15} cm^{-3} , uniformity better than 2%, define baseline choice(s)

Demonstrate seeding in experimental tests, define baseline

Dec 2014

Demonstrate 1% uniformity and complete operational plasma cell(s)

installation of switch/delivery into TT61 by end of LHC shutdown

Aug 2015

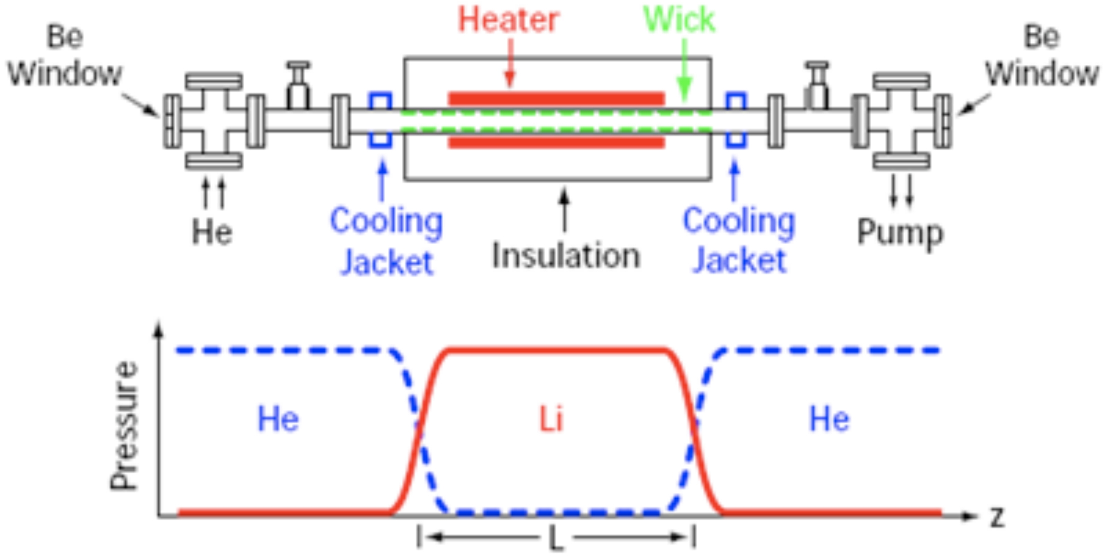
Installation of beam lines, experimental area

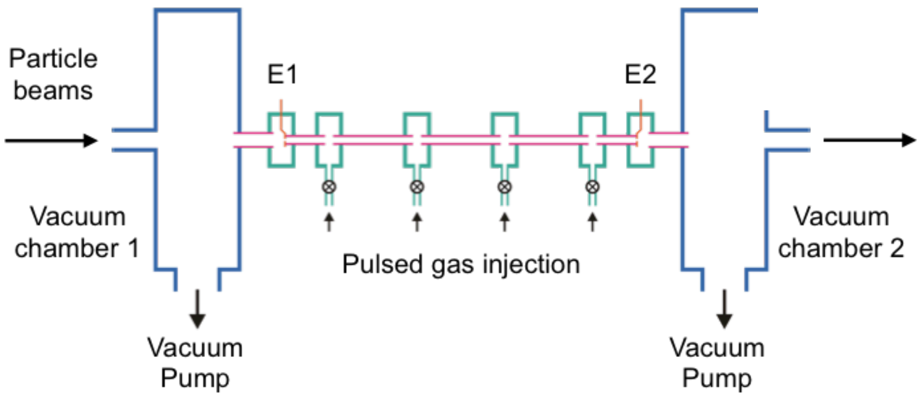
Sep 2015

Beam commissioning, first beam to plasma

Plasma Cell ideas:

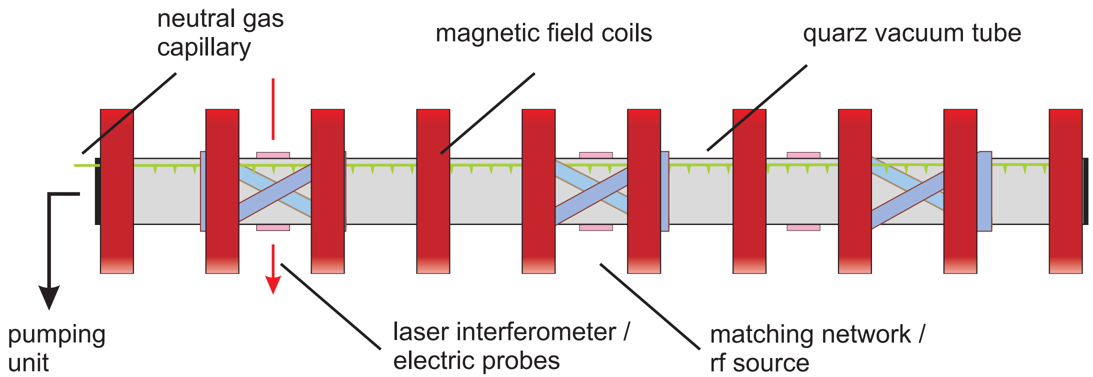
Heat pipe oven, a la SLAC experiment:
Max Planck Institute for Physics





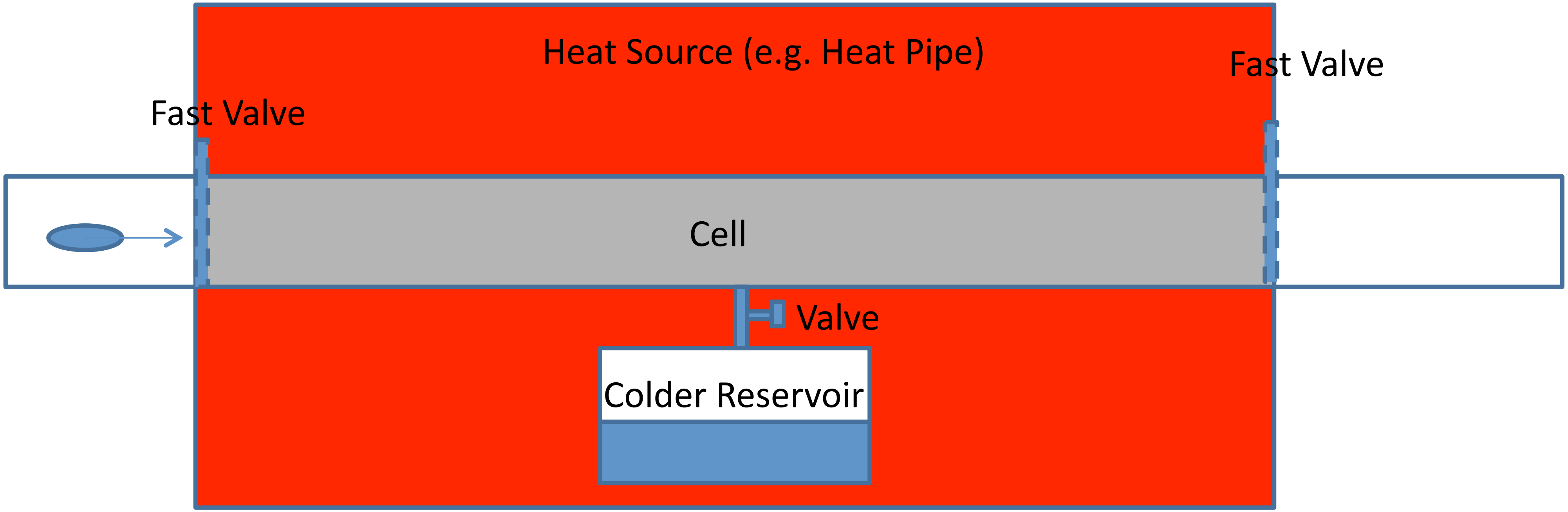
Discharge: IST, Imperial College

Helicon – Max Planck Institute
for Plasma Physics



Plasma Cell ideas:

Metal vapor cell: MPP



More on this later …

MPP Specific Activities

Patric Muggli, Olaf Reimann, Hans von der Schmitt, Frank Simon, Allen Caldwell
Erdem Öz, Roxanna Tarkeshian
Scott Mandry, Tobias Rusnak, Botho Paschen

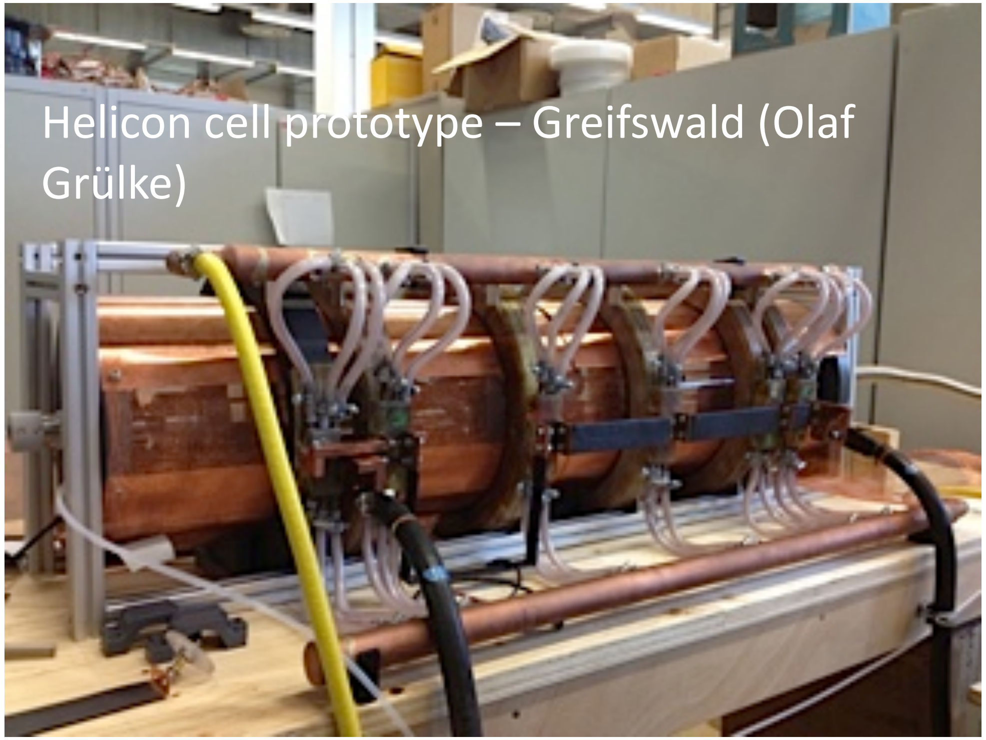
Planning the CERN experiment

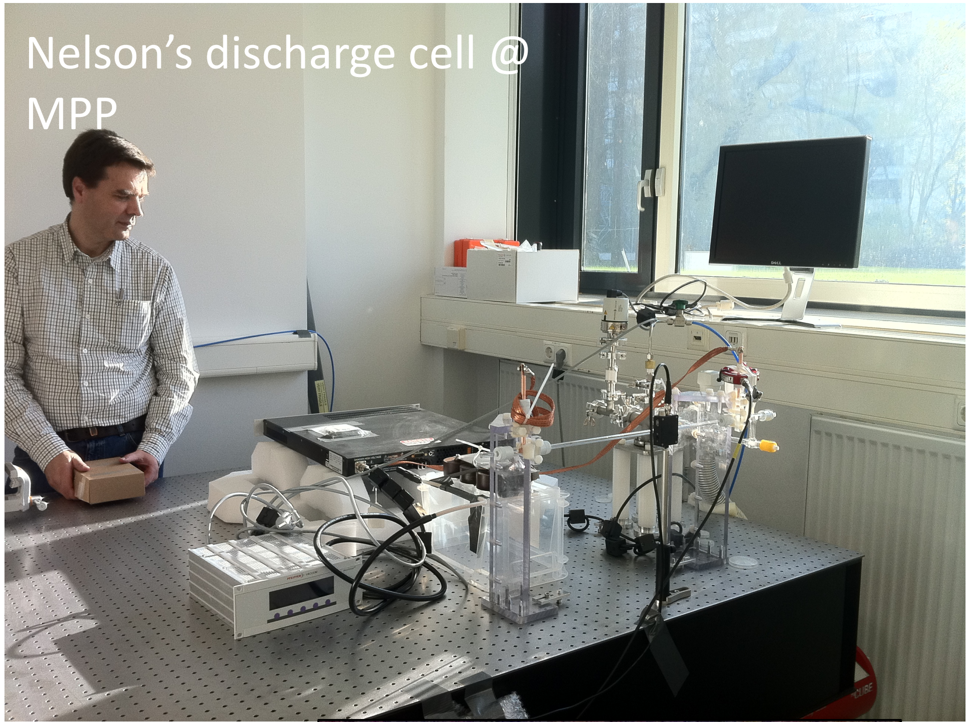
Development of novel plasma cells

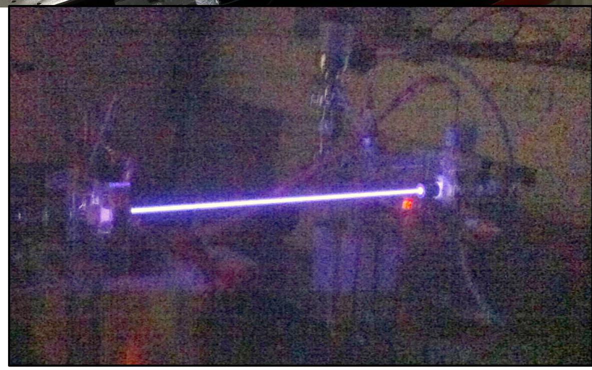
Development of novel diagnostic tools

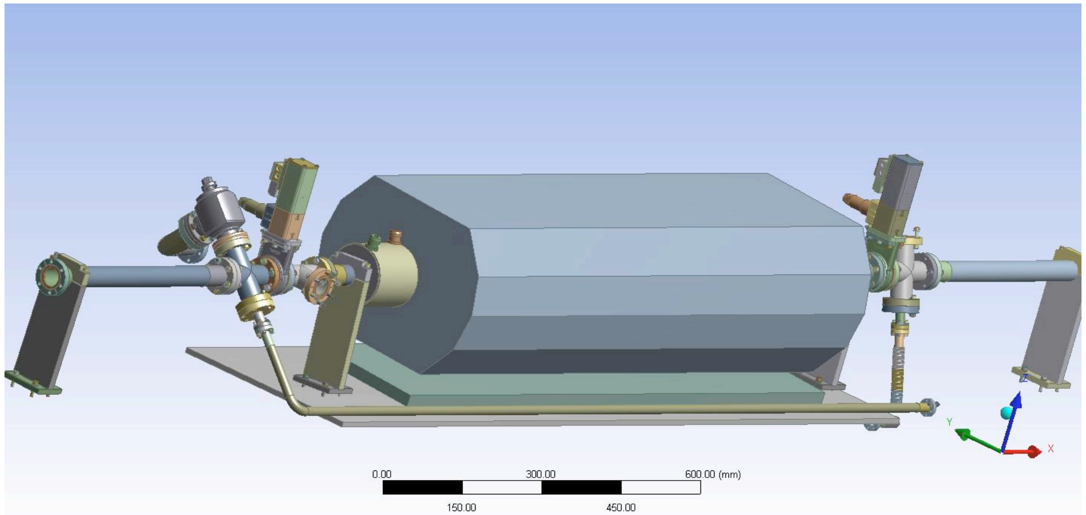
+ Patric's activities at BNL & SLAC

Plasma cell R&D


Helicon cell prototype – Greifswald (Olaf Grülke)

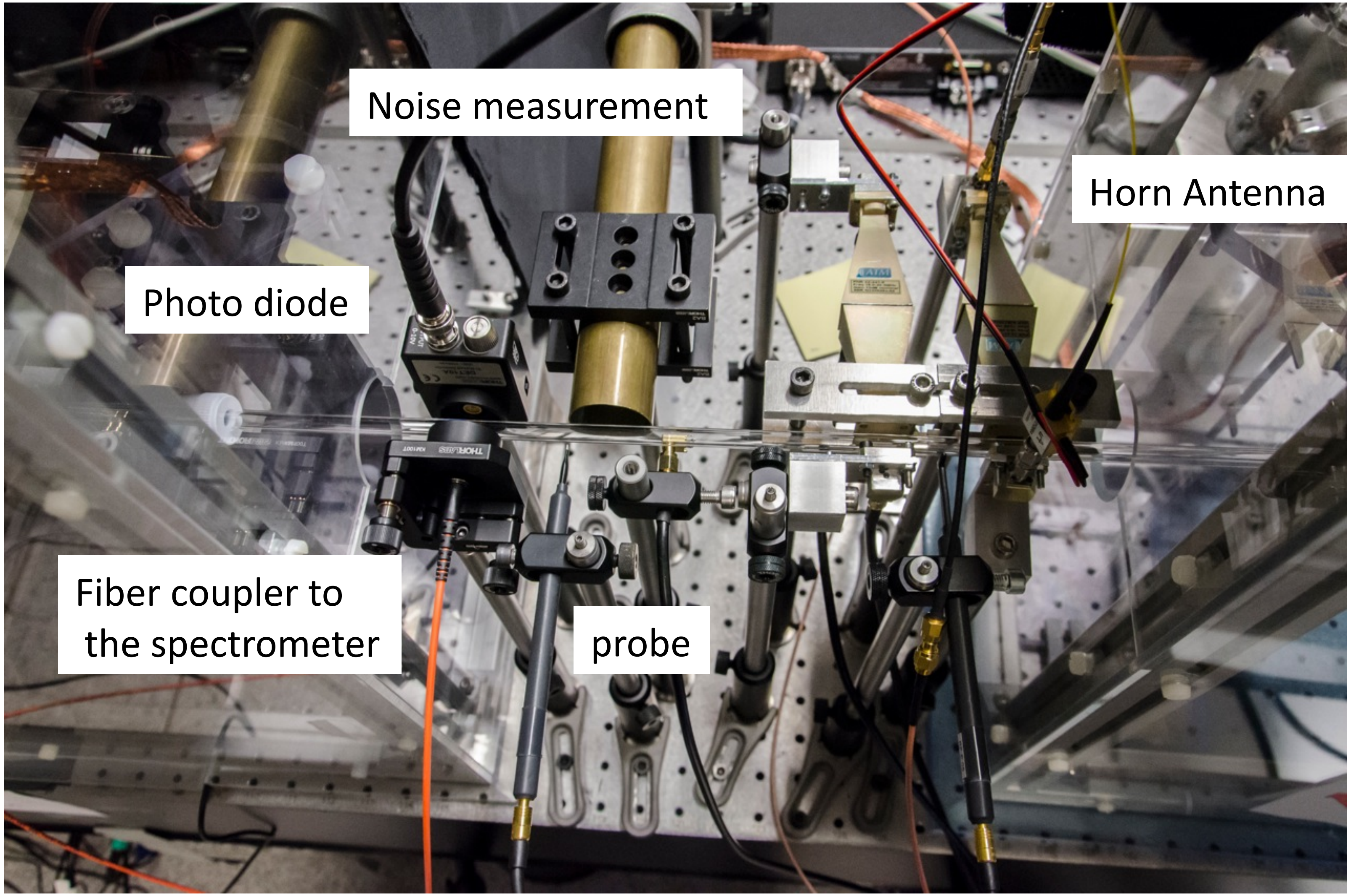

Nelson's discharge cell @ MPP





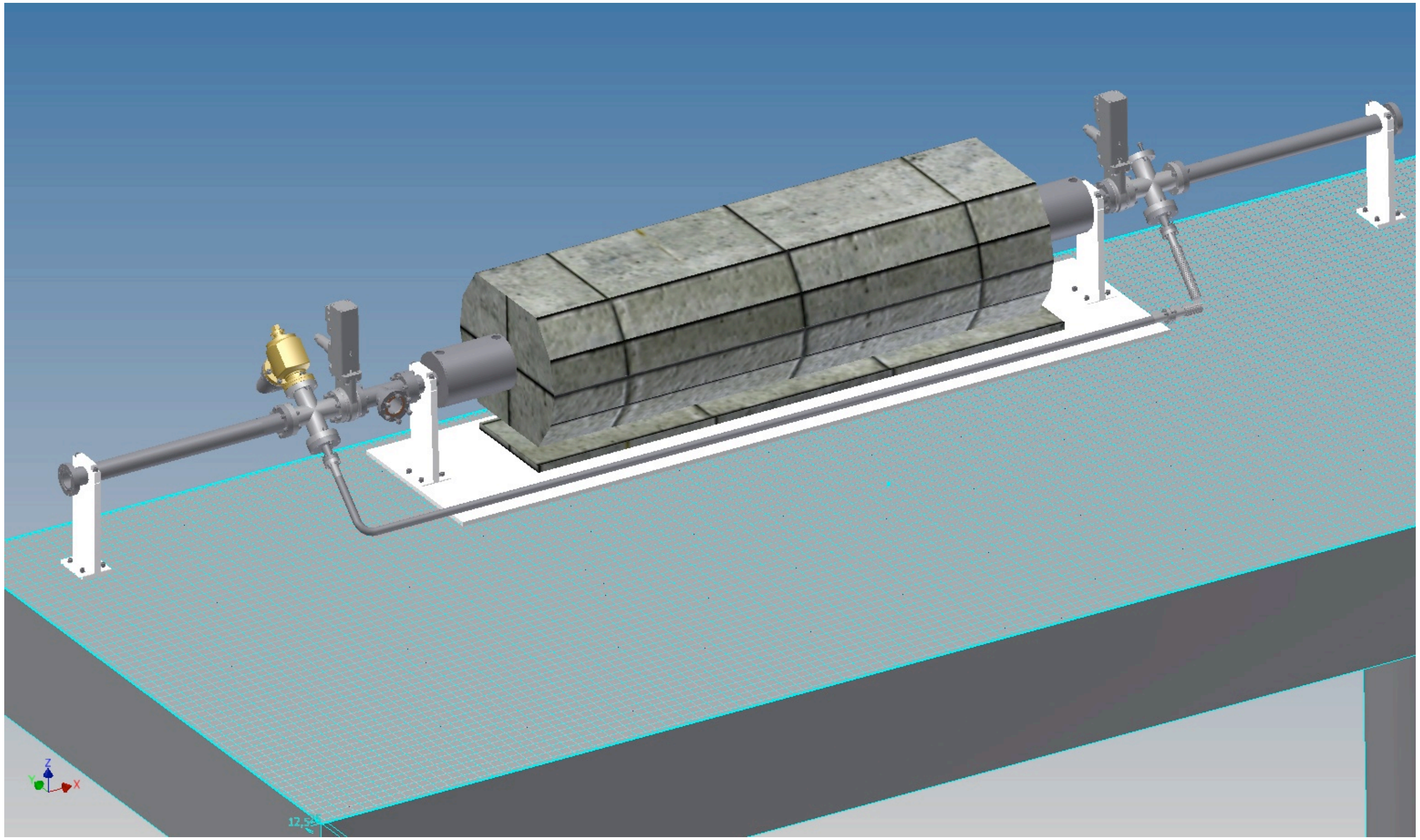
Heat pipe oven concept + vapor cell
E. Öz, P. Muggli

Measurements with discharge cell

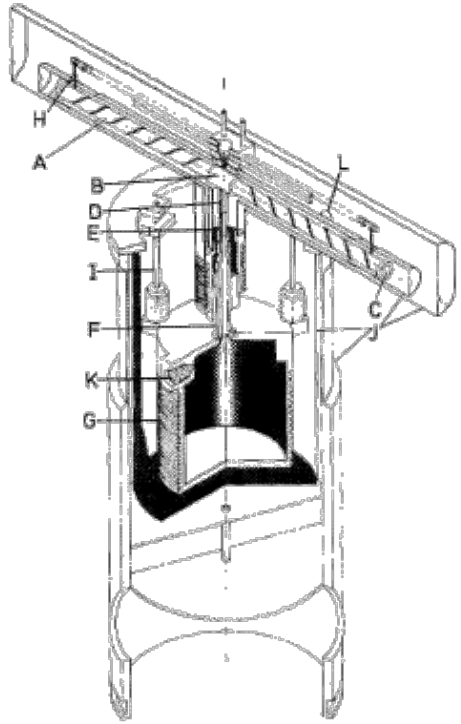


Heat Pipe Oven

SLAC style, under development at MPP although it will probably not be used at CERN: Probably Rb and not Li vapor. Will be used to study density uniformity (fluid---molecular flow)



Metal Vapor Cell



under design. Probably Rb rather than Li

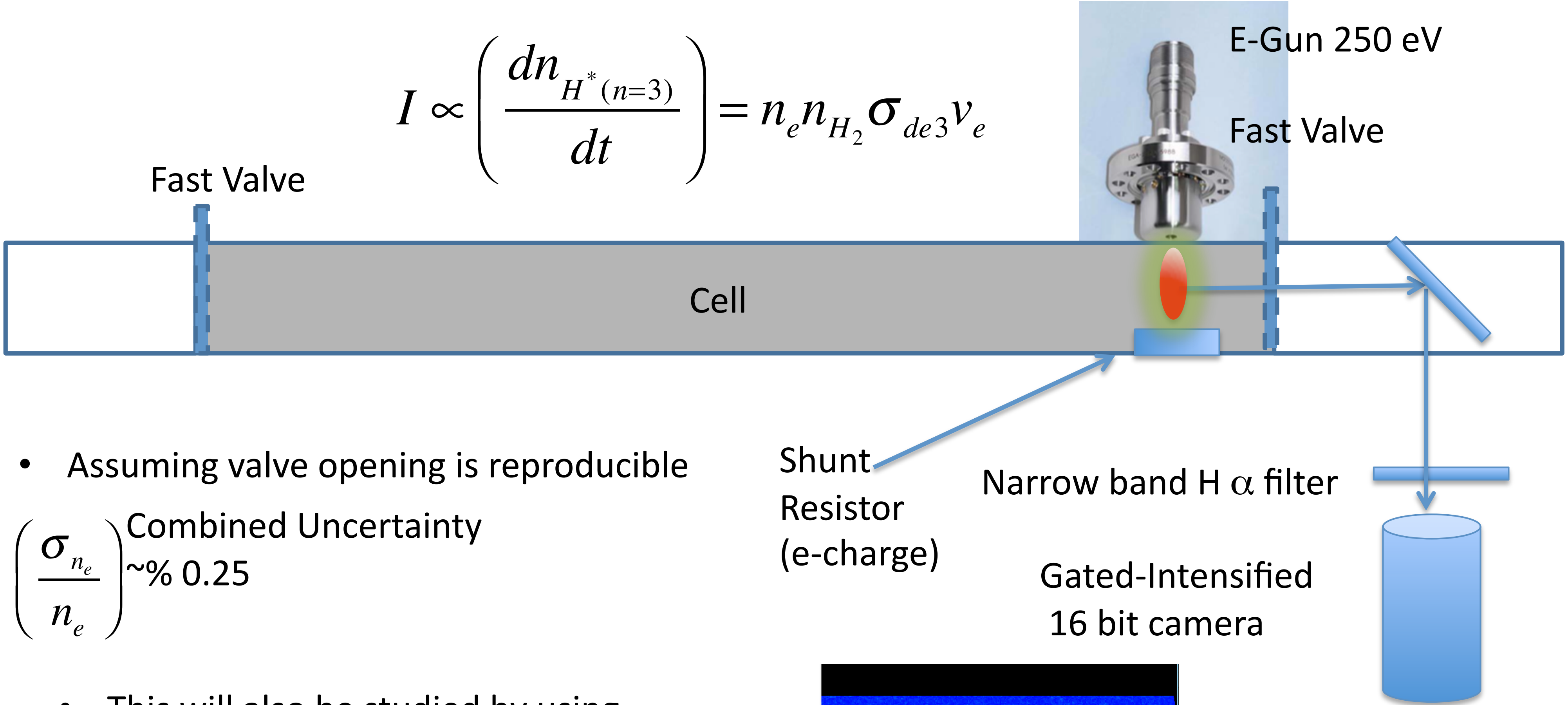
No buffer gas, no wick, no liquid - just the vapor as the ideal gas
$\Delta T/T=\Delta n/n$ - temperature stability is key.

But - Alkali metals are extremely corrosive, hard to confine, blacken glass, quartz
Requires special sealing, special materials especially for windows, high failure rate
Literature: Vapor cells with separate liquid reservoir (coldest point) : liquid provides density control

Looking into valve technology for laser, beam; evaluating necessary speed and other conditions to maintain density uniformity.
Laser parameters for ionization/seeding have been worked out. Acquire laser 2013.

Characterization of Density Non-Uniformity Caused by Valves : Electron Beam Fluoresence*

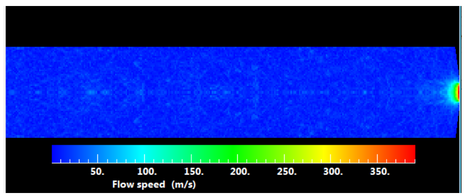
$$I \propto \left(\frac{dn_{H^*(n=3)}}{dt} \right) = n_e n_{H_2} \sigma_{de3} v_e$$



- Assuming valve opening is reproducible

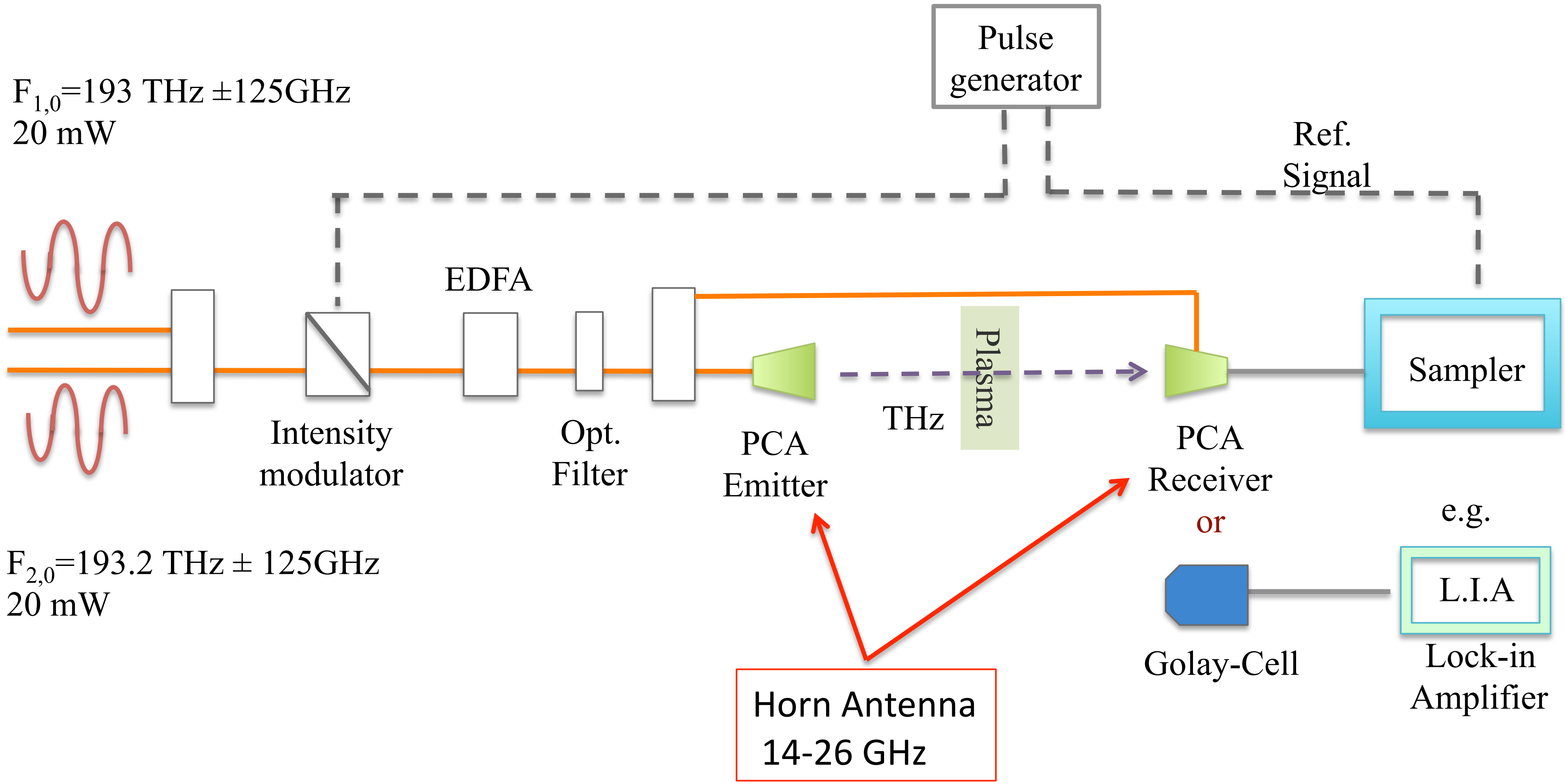
$\left(\frac{\sigma_{n_e}}{n_e} \right)$ Combined Uncertainty ~% 0.25

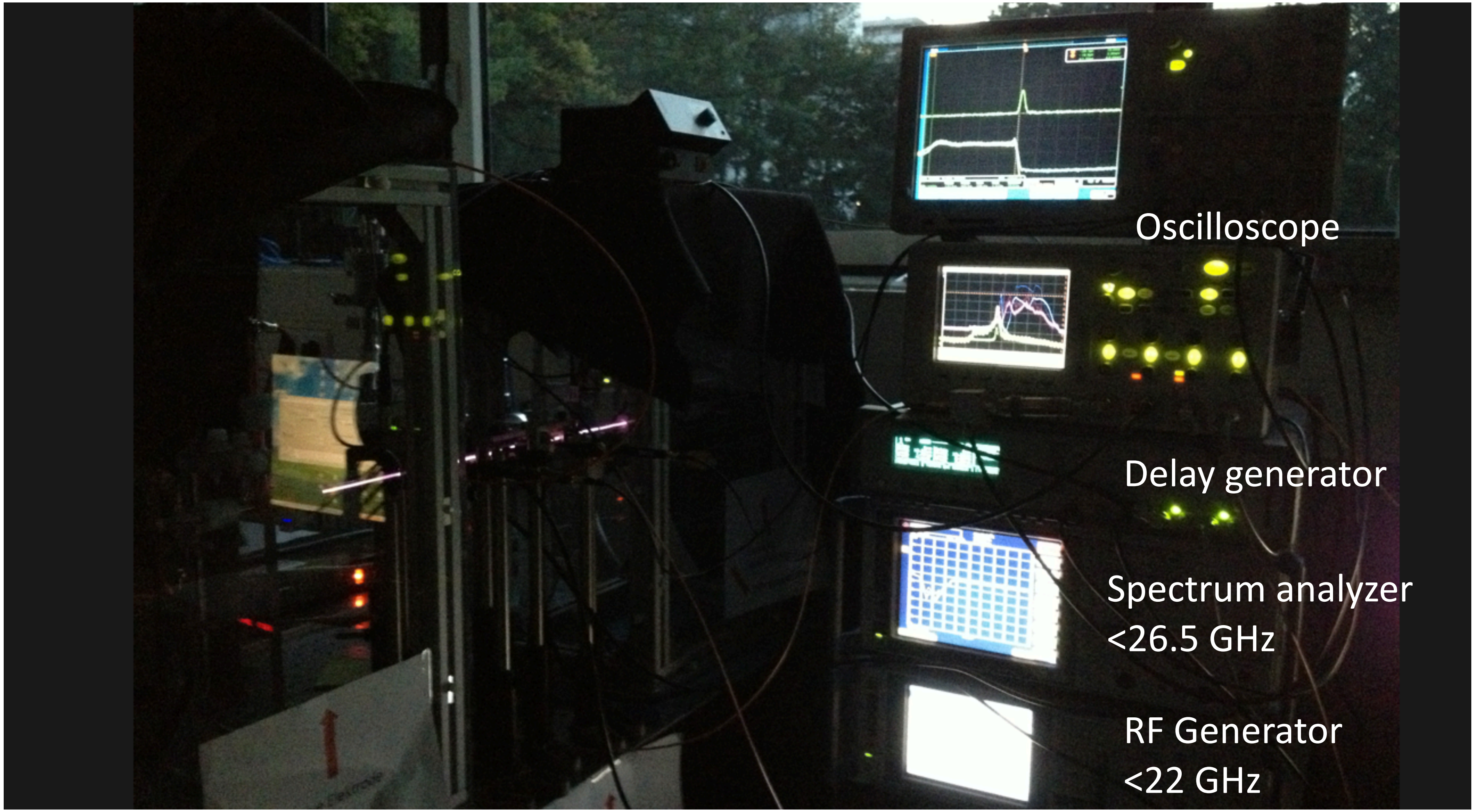
- This will also be studied by using (DSMC) Direct Method Monte Carlo Simulation



*Measuring the density of a molecular cluster injector via visible emission from an electron beam **D.P. Lundberg et al**, Princeton Plasma Physics Laboratory Rev. Sci. Instrum. 81, 10D707 (2010);

Plasma density measurement via GHz transmission



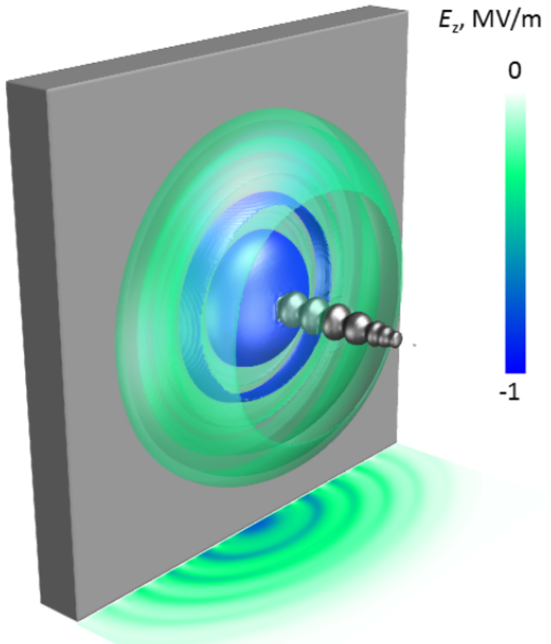

Oscilloscope
Delay generator
Spectrum analyzer
<26.5 GHz
RF Generator
<22 GHz

Example diagnostic study:

Transverse Coherent Transition Radiation (TCTR)

Introduced by A . Pukhov

- Coherent Transition Radiation emitted radially around a charged beam along the surface of a (metallic) screen
- Electric field component normal (to the screen)
- Dipole-like radiation pattern
- Can be modulated by beam density



Picture taken from the paper

Transverse coherent transition radiation for diagnosis of modulated proton bunches

A. Pukhov and T.Tueckmantel
Insitut fuer Theoretische Physik I, Universitaet Duesseldorf, 40225 Germany

Transverse coherent transition radiation (TCTR) emitted by a relativistic particle bunch traversing a conducting surface is analyzed. The bunch emits dipole-like radiation in the direction transverse to the bunch axis when the beam radius is smaller than the radiation wavelength. The radiation wavelength is defined by the longitudinal structure of the particle bunch. The particular case of proton bunches modified by propagation in plasma, but still carrying an unmodulated current is considered. Radius-modulated bunches with a constant current emit axially symmetric radiation. Hosed bunches emit antisymmetric radiation in the plane of hosing. The TCTR field amplitude may reach 100 kV/m for the existing proton bunches.

PACS numbers: 41.60.Dk, 52.40.Mj

Coherent transition radiation (CTR) is one of the most common techniques used for diagnosis of a longitudinal structure of charged particles bunches [1–5]. The method particularly demonstrated its power to characterize accelerated electron bunches in laser-plasma experiments [6–8]. An elementary charge propagating through a medium with a particular dielectric permittivity is dressed by a field matched to that medium. When the charge traverses a sharp boundary of two media with different permittivities, its field must be adjusted. The unmatched field can be radiated. The strongest radiation is observed when a charge passes a boundary between a conductor and vacuum. A point-like relativistic charge with the relativistic factor γ emits a radiation burst that is collimated within a cone with the opening angle $\theta \approx 1/\gamma$ around the axis, although the emission is exactly zero in the propagation direction itself. The radiation is broadband. A bunch of particles can emit this radiation coherently at the wavelength comparable with its longitudinal structure.

Recently, a concept of proton bunch-driven plasma wake field accelerator has been put forward [9–11]. In this concept, a long proton bunch is sent through plasma where it undergoes self-modulation at the plasma wave period and excites a strong resonant wake field. A test experiment is in preparation at CERN. One of the experimental challenges will be the detection and characterization of the proton bunch modulation after it exits the plasma cell.

The nature of the proton bunch modulation is such that the proton bunch radius is modulated, but the total bunch current remains the same in each cross-section. For this reason, there will be no signatures of the proton bunch modulation in the forward coherent transition radiation. The classic forward CTR is cast useless in this case. Moreover, it is important in the experiment to distinguish between the axisymmetric modulation mode when the radius of the proton bunch is changing periodically [11] and the possible hosing mode when the proton bunch centroid oscillates periodically in the transverse plain [12].

Below we show that the transverse coherent transition radiation (TCTR) does contain the signature of the bunch modulation and allows to distinguish between the axisymmetric modulation mode and the hosing. The TCTR is emitted perpendicularly to the particle bunch propagation direction and its amplitude does not depend on the particles γ–factor as soon as it is large enough.

ORIGIN OF TRANSVERSE TRANSITION RADIATION

Let us consider a transition radiation emitted by a particle bunch as it traverses normally a conductor plate. The interaction geometry is illustrated in Fig. 1. When an elementary charge dq exits from the conducting plate in the normal direction with the velocity $\mathbf{v}$, the radiated field is given by the formula (63.8) from the Landau textbook [13]:

$$\mathrm{d}\mathbf{E} = \frac{dq}{c^2\left(R - \frac{\mathbf{R}\mathbf{v}}{c}\right)^3}\mathbf{R} \times \left[\left(\mathbf{R} - \frac{\mathbf{v}}{c}R\right) \times \frac{d\mathbf{v}}{dt'}\right] + \frac{dq}{c^2\left(R + \frac{\mathbf{R}\mathbf{v}}{c}\right)^3}\mathbf{R} \times \left[\left(\mathbf{R} + \frac{\mathbf{v}}{c}R\right) \times \frac{d\mathbf{v}}{dt'}\right] \quad (1)$$

where t' is the retarded time so that

$$t' + R(t')/c = t. \quad (2)$$

The second term in Eq. (1) is generated by the image of the physical charge in the conducting plate.

When the elementary charge is inside the metal plate, its field is completely screened. Thus, the current is created abruptly when the charge exits into the free space. We can write for the velocity $\mathbf{v}(t') = \mathbf{v}_0\Theta(t' - t_0)$, where t_0 is the time the charge exits into vacuum and $\Theta(t)$ is the Heaviside step function.

The denominators in Eq. (3) suggest that a point-like charge emits the strongest field at the angle $\theta \approx 1/\gamma$ around the propagation direction. Yet, we will be not interested in the emission in this direction, because it does

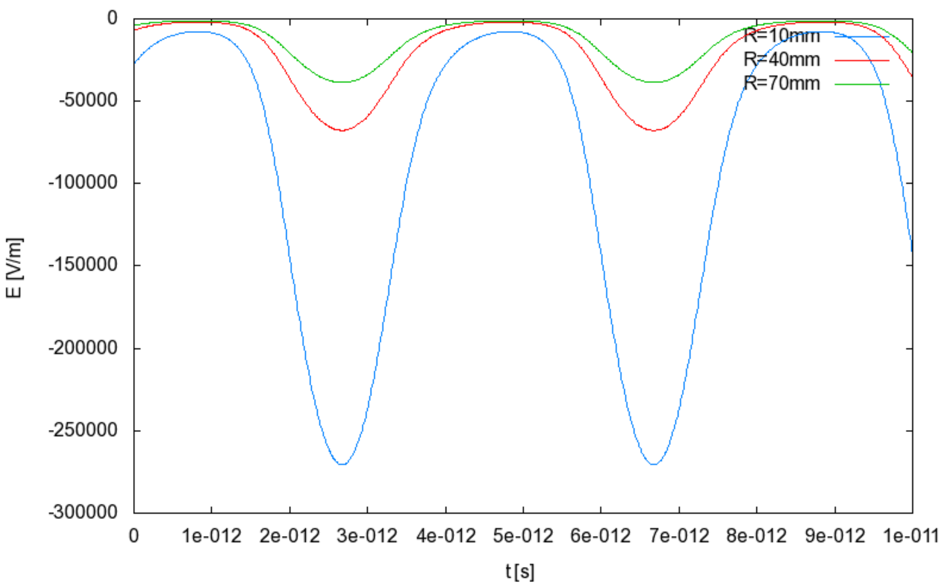
TCTR in combination with EO-sampling

- Electric fields with amplitudes up to hundredths of kV at a distance of 10mm
- Signal is to the first order proportional to the beam density
- High frequencies (several hundredth GHz)

  $\longrightarrow$ Make use of electrooptic sampling
- But: No simple frequency response curve

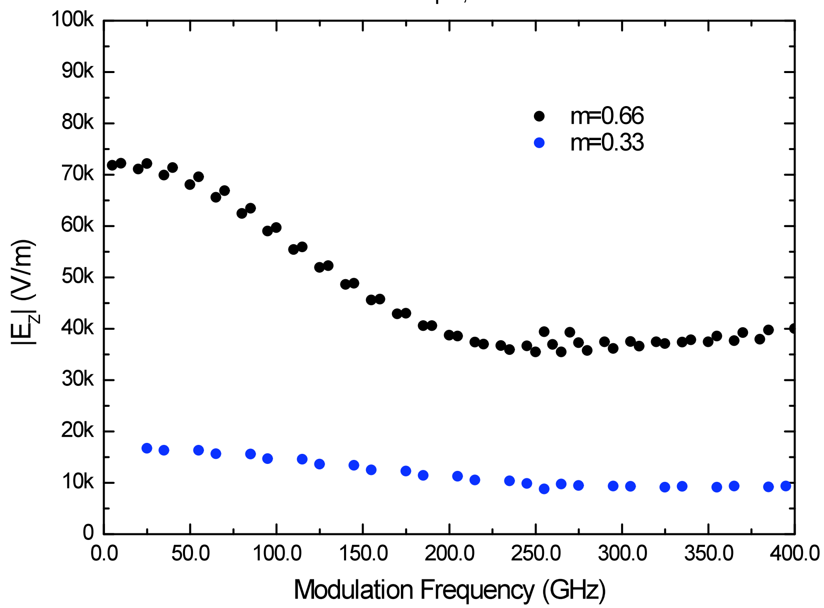
$$E_z(\omega, R_0) = \frac{ev_0^2}{\pi c^2 R_0} \exp(j\omega(-\frac{R_0}{c}) \int \int \exp(j\omega \frac{\rho}{c} \cos(\phi)) \tilde{n}(\omega, \mathbf{r}) \rho \, d\rho \, d\phi$$

Typical E-field for TCTR at different radial distances



1. Harmonic of detected TCTR-field

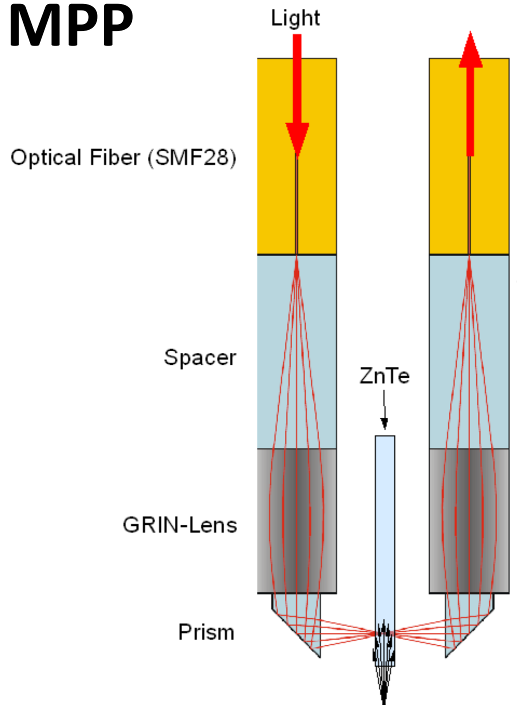
Mean beamradius: 600µm, radial distance: 40mm



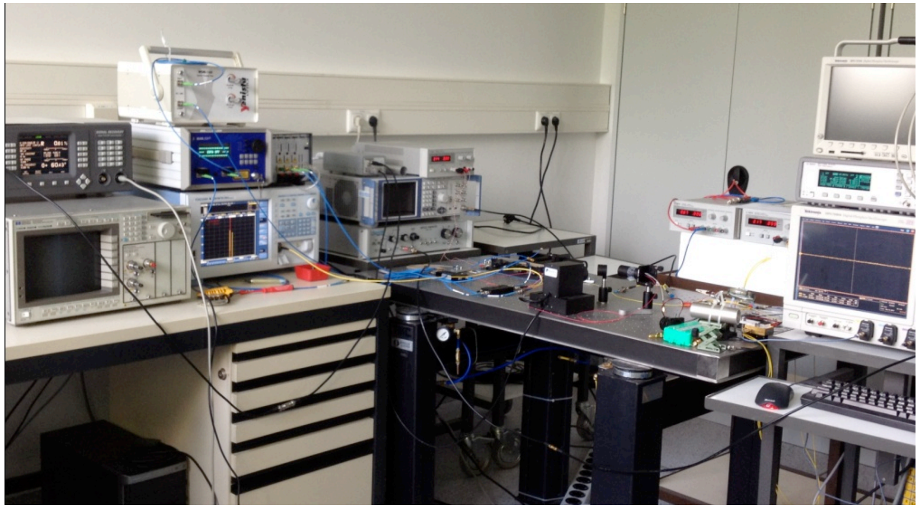
Development of EO-sampling (for TCTR) at MPP

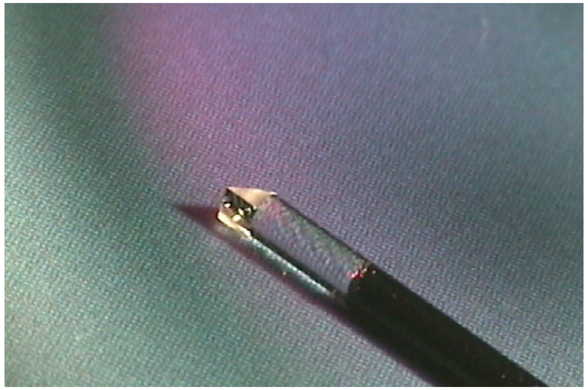
- Using dispersive Fourier-transform
- First test setup is working fine
- Development of special probes in the near future

Probe setup with a “closed” optical path using GRIN-Lenses and prisms:
Possible length of probe in longitudinal (beam) direction: < 1cm



EO-sampling and plasma density measurement at MPP





GRIN-Lens with prism (GRINTECH)

Conclusions

- Proton-driven wakefield acceleration has appealing features
- AWAKE collaboration formed, preparing CDR for CERN experiment
- Active R&D going on in many places, including at the MPP