The Hungarian contribution to the planned CERN AWAKE experiment

5 December 2013, Zimányi SCHOOL'13 Budapest

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Outline

- Introduction of the problem

-One possible solution - the AWAKE experiment

(some slides are taken from Patric Muggli & Edda Gschwendtner)

-Our contribution experimental and theoretical

(it is a group activity not only mine, see later)

The field of interest

Recent accelerator technology
(accelarating in vacuum with radio frequency)
like LHC ring reached its physical, geometrical limits
LHC ring is 27 km long,
the max. accessible accelarating gradient less than 50 MV/m in ring

What is the way out?
Vacuum $\rightarrow$ plasma
Radio frequency $\rightarrow$ quick charged particle/short laser pulse

Different accelaration mechanisms

Laser-driven plasma-based accelarations

laser wake field accelaration (LWFA),

plasma beat wave acceleration (PBWA)

self-modulated LWF

multiple laser pulses in PBWA

Particle-driven plasma-based accelarations

proton-driven plasma wake-field (our field of interest)

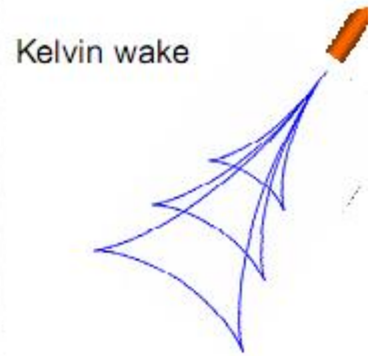
electron-driven plasma wake-field

Dielectric Wall Accelarator

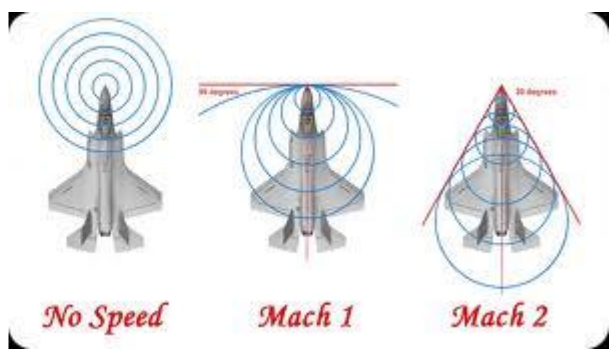
relativistic particle beam wake in a non- linear dielectric wave guide

Wakefield

All particles in the medium participate = collective phenomenon



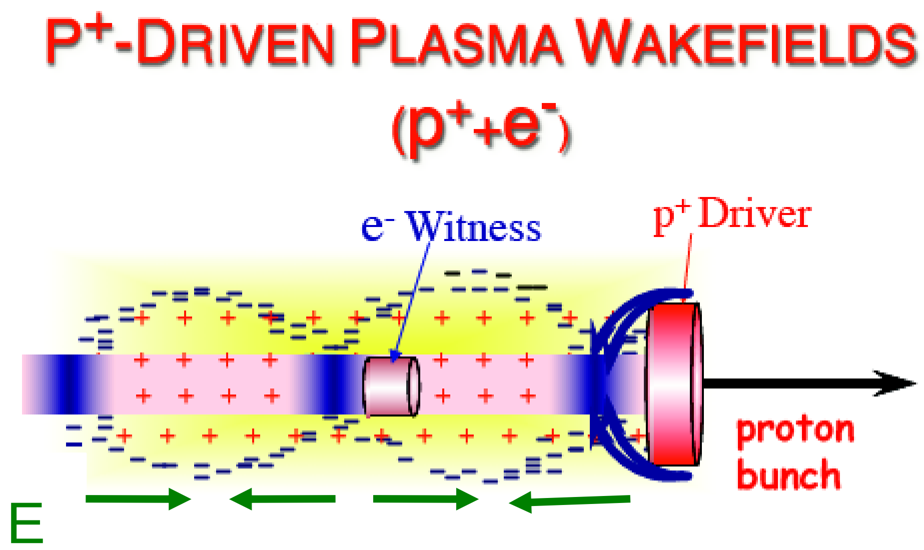
No wave breaks and wake **peaks** at v≈c



Mach cone

The idea of the AWAKE Experiment

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



Short proton bunches are needed: $L \approx 100\ \mu m$

Not possible to create directly

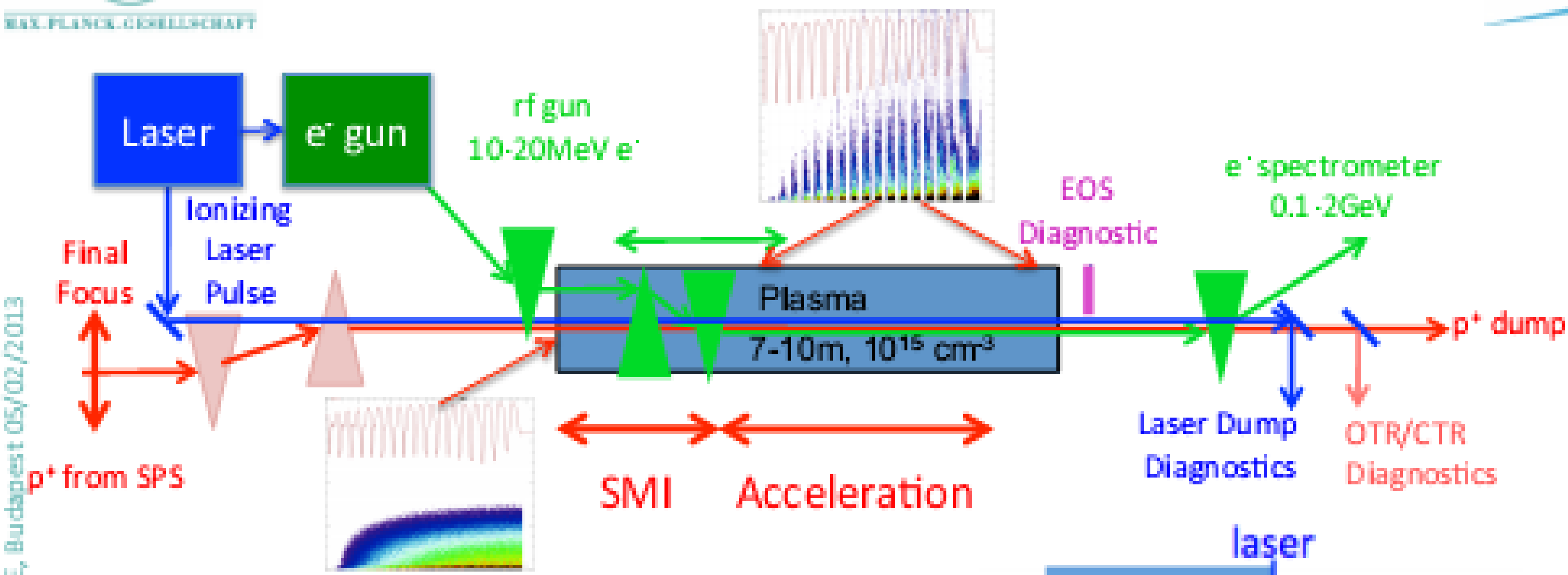
Additional short laser pulse is used to

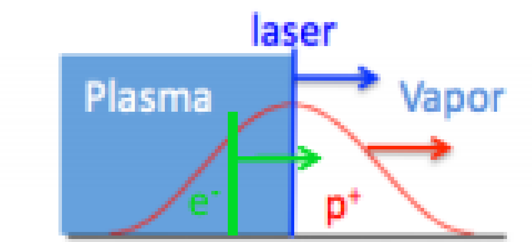
1) create the Rb plasma with single-ionized atoms

2) and the self-modulation is used to create short proton bunches

(Fig. Is taken from Patric Muggli)

BASE-LINE EXPERIMENTAL SETUP





- Laser ionization of a Rb metal vapor, 7-10m plasma, $n_e=10^{14}$-10^{15}cm^{-3}
- Injection of 10-20MeV test e- at the 3m point (SMI saturated, $v_\phi=v_{p+}$)
- SMI-acceleration "separated"
- 0.1-5GeV electron spectrometer
- OTR + streak camera, electro-optic sampling for p⁺-bunch modulation diag.
- Additional optical diagnostics

Plasma Source Requirements

MAX-PLANCK-GESELLSCHAFT

AWAKE

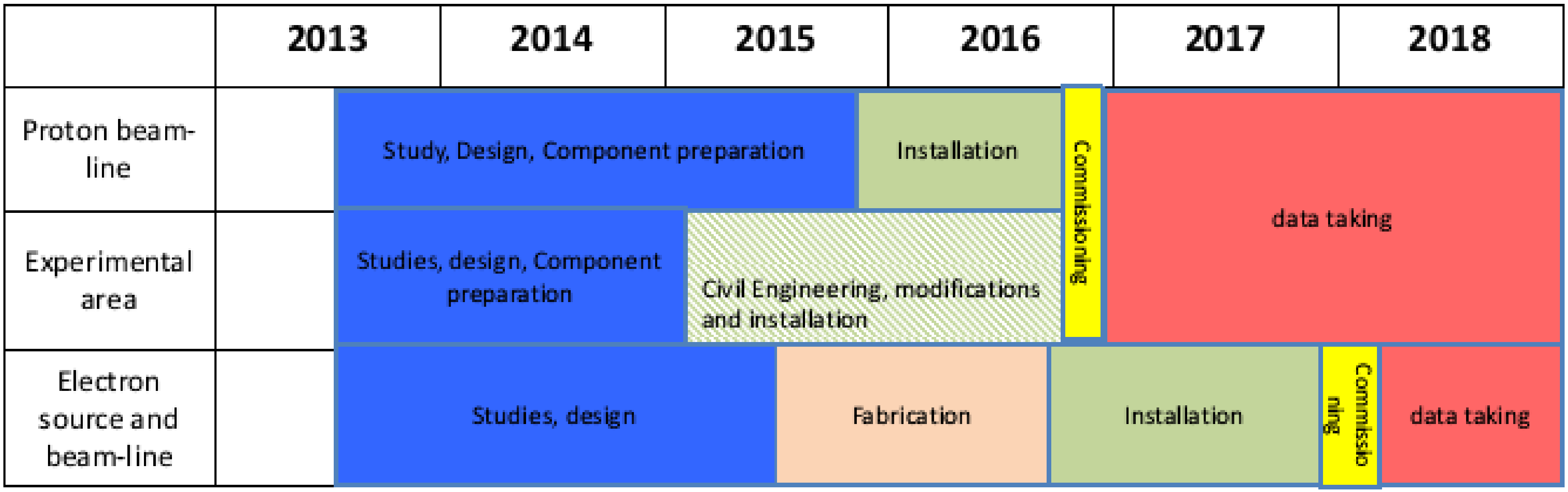
- Plasma formed by field ionization of Rubidium (Rb) vapor
- Above threshold (~10^{12} W/cm^2) ionization= 100%, threshold process

  Plasma density = vapor Density (n)
- Short proton bunches can drive maintain GeV/m accelerating gradients over many m of plasma
- Producing short proton bunches not possible today w/o major investment. Not an option for the short term
- Using transverse two-stream instability (Self-modulation Instability, SMI)
- microbunches are naturally spaced at the plasma wavelength, and act constructively to generate a strong plasma wake*
- SMI resonance effect and ...
- Acceleration of an electron buch in this wake requires 0.2% uniformity** (σ_z=12cm) at least until electrons reach high energy i.e. first few MeVs
- This requirement scales inversely with the number of oscillators
- 1/(Number of Microbunches)

Plasma density requirement: $\frac{\Delta n}{n} \leq 0.002$ Homogenous ionization is needed!!!

Time-Scale as in the CERN Medium-Term Plan

Time-scale for AWAKE in the MTP



Needed CERN resources:

Costs: 8.5 CHF

Person-Years: 34.2 PY

→ Budget and manpower profile for 5 years

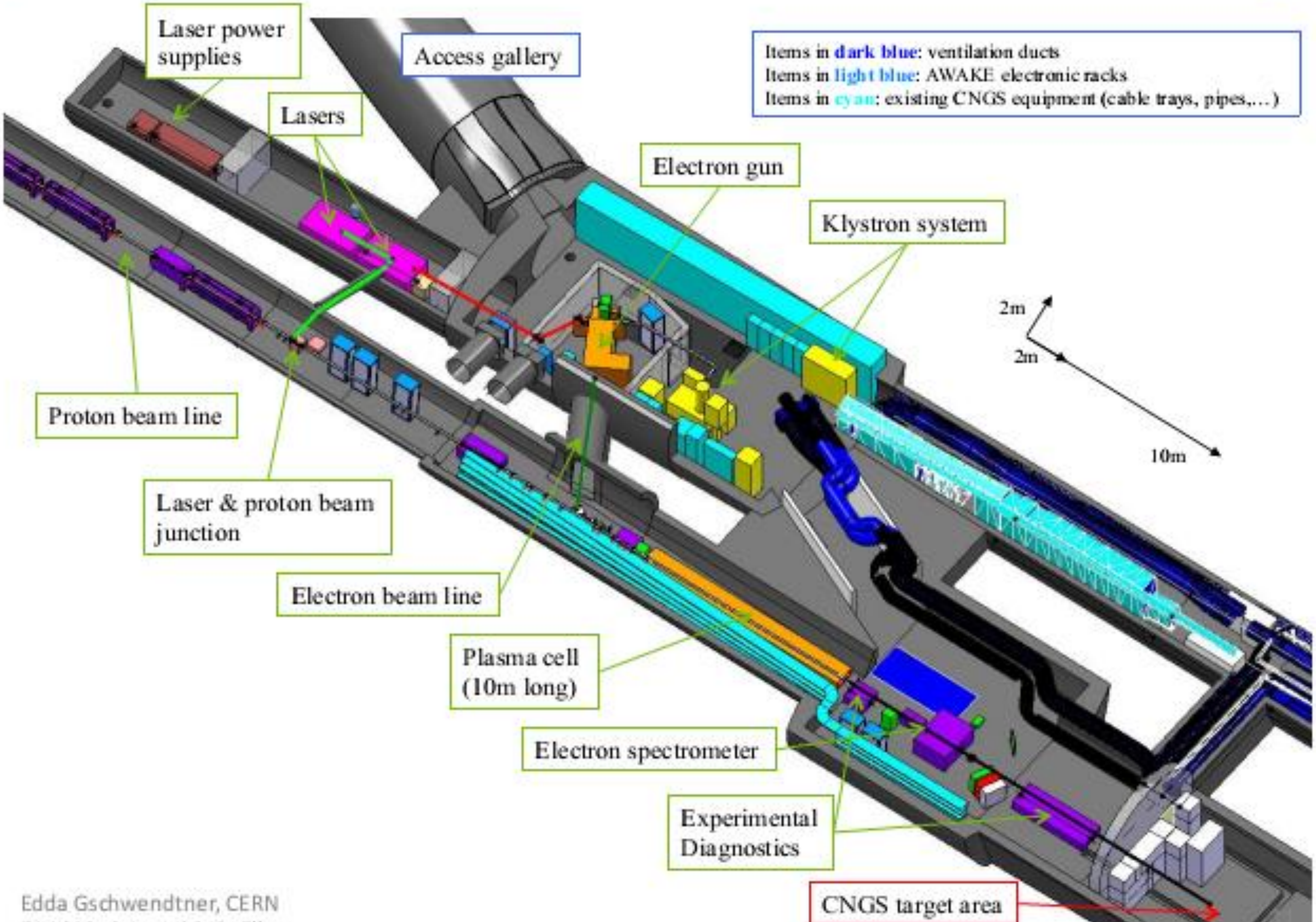
Birdeye view of the CNGS- AWAKE Spot

CNGS: Cern Neutrinos to Gran Sasso project, Ran between 2006 - 2012

AWAKE at CNGS

AWAKE at CNGS

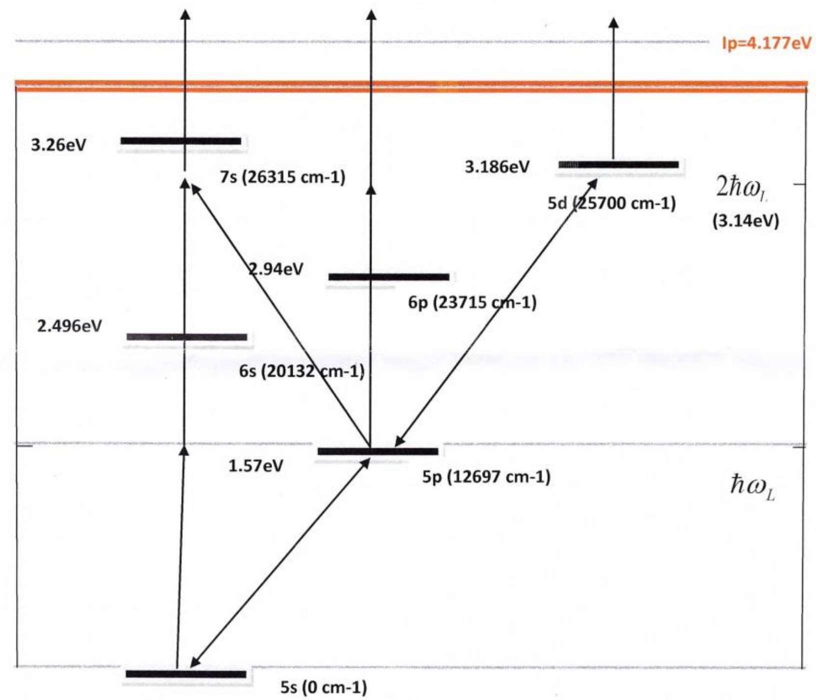
Layout of the AWAKE Experiment



Our contribution to improve the AWAKE Experiment

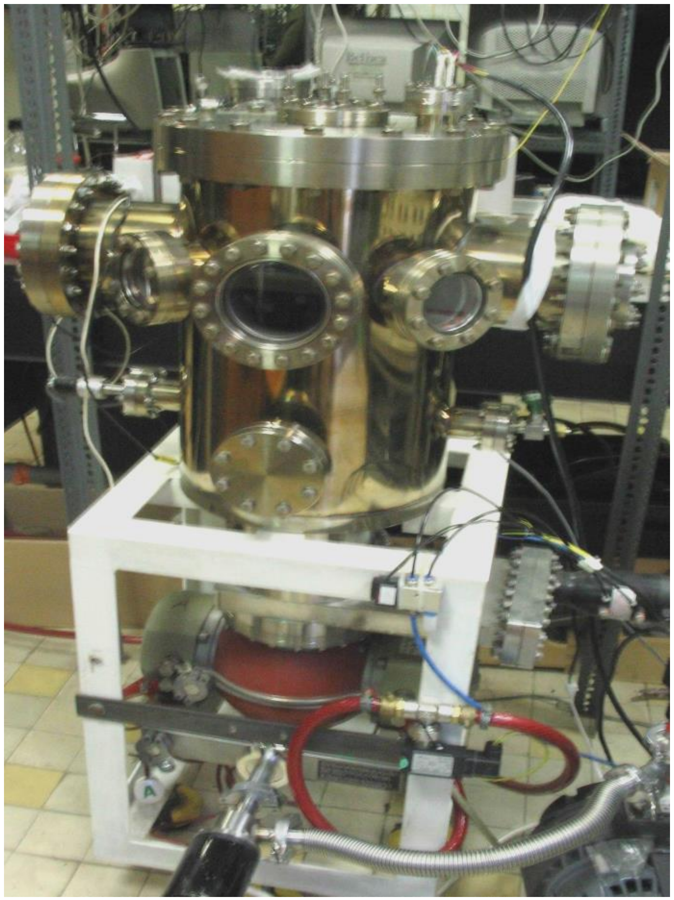
Idea:
use a short chirped laser pulse to populate the 7s and 5d two-photon resonant excited states
to enhance the total single-ionization cross sections in the
GeV proton – Rb collisions and create a homogeneous plasma

(Model: with a laser-atom calculation coupled to ion-atom collision including propagation phenomena)

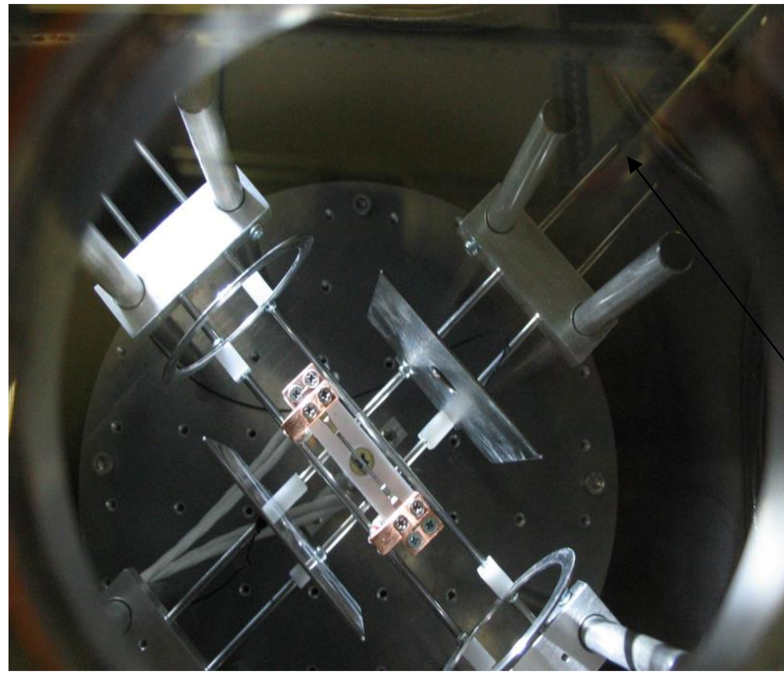


Rubidium-85 energy levels

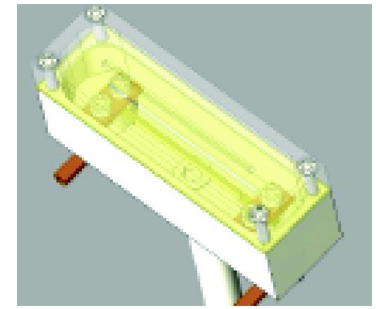
The experimental setup



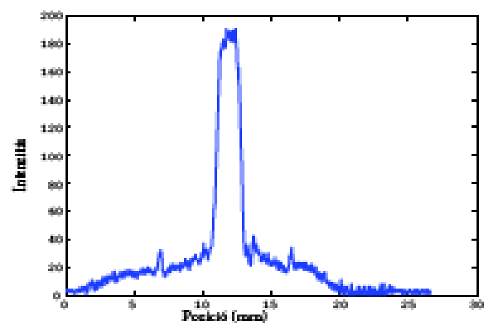
The vacuum chamber

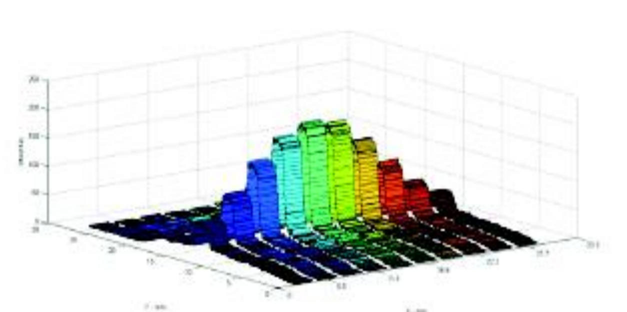


MCP detector



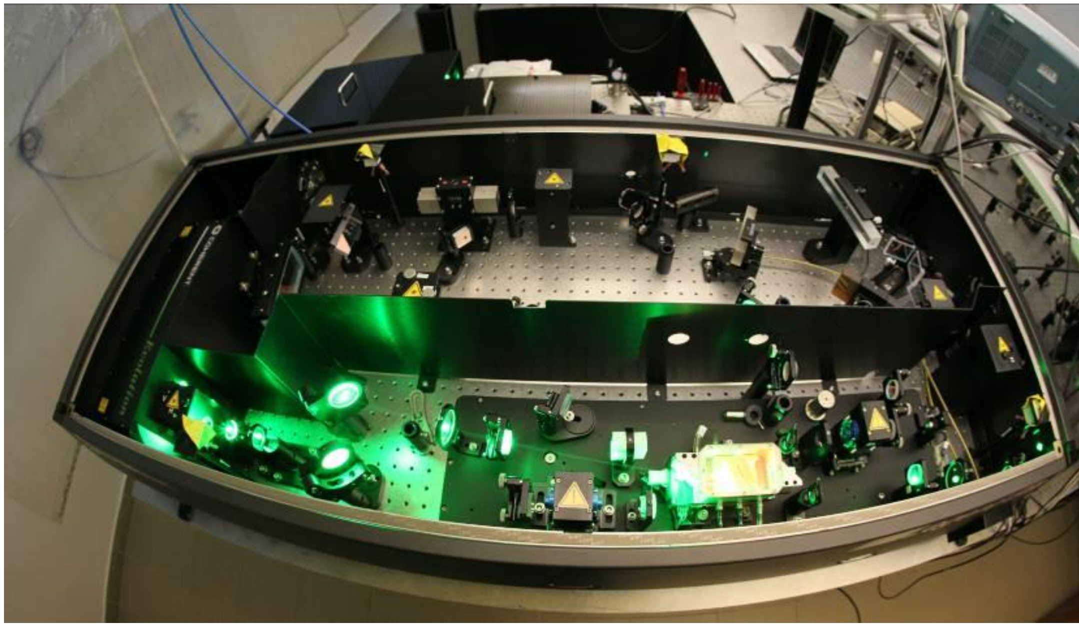
Rb dispenser





The Rb atom beam distribution above the slit

The laser system



Primary laser source
- fs-duration system:
Ti:sapphire oscillator + regenerative amp.

the laboratory is used for
HHG experiments, surface plasmons

Clean room: 3000-4000 particles / foot^3

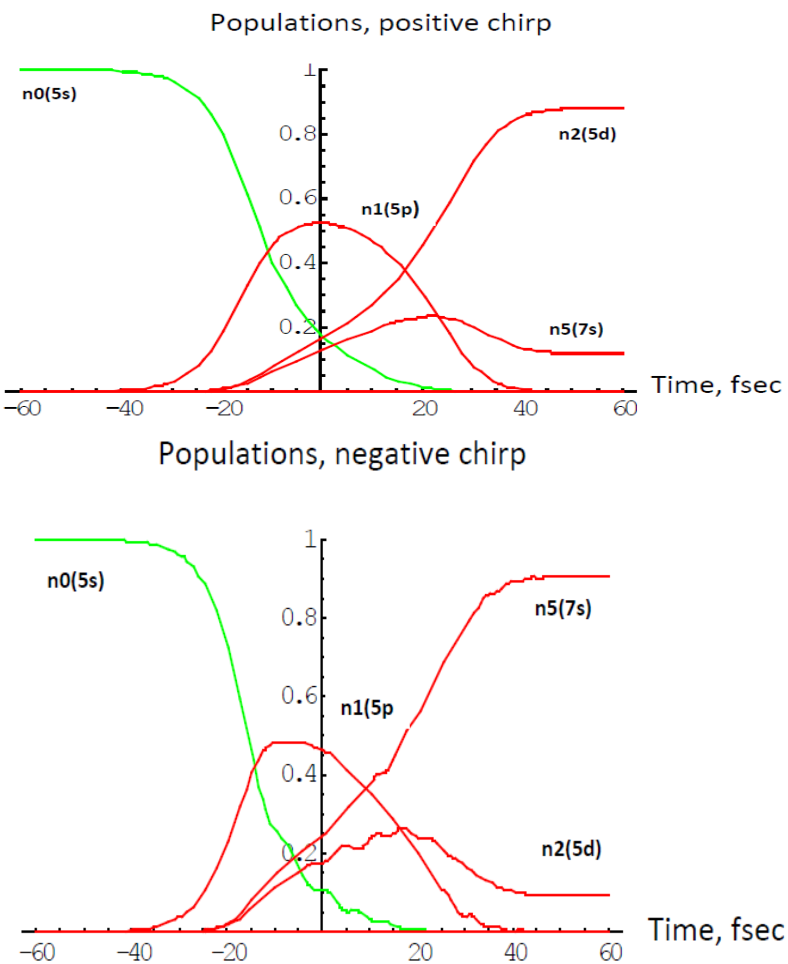
Output parameters of the laser system

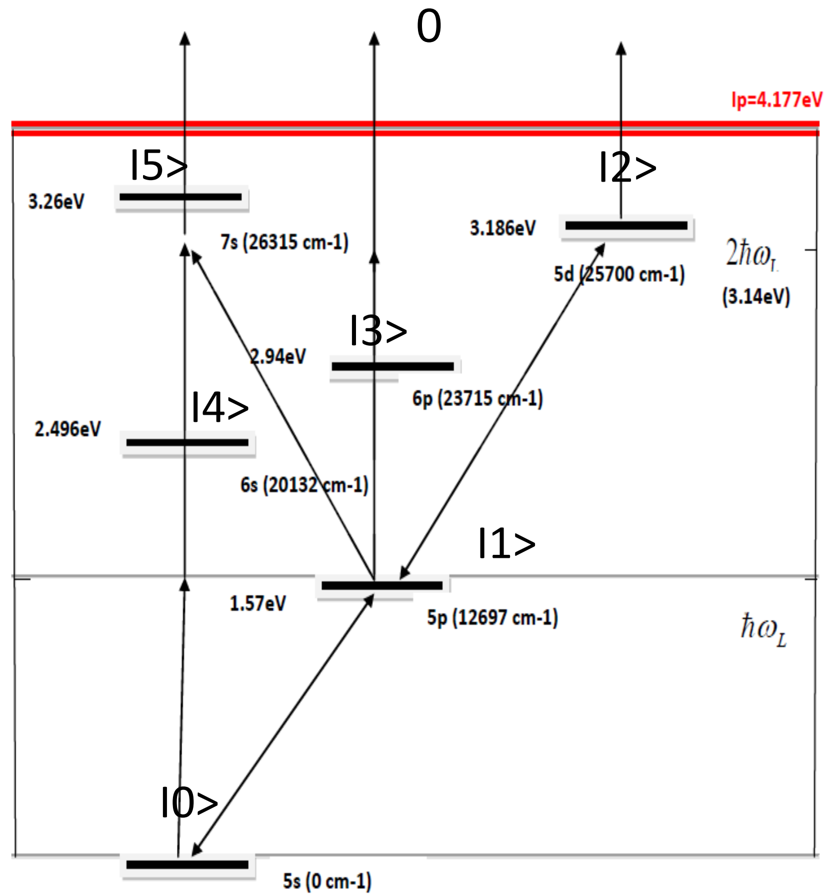
Parameters	Typical values
Mean wavelength	806 nm
Average Power	4.1W
Beam Diameter:	9 mm ($1/e^2$,Gauss)
Polarisation:	Linear, vertical
Repetition Rate	1 kHz
Pulse duration (FWHM):	35 fs
Energy. stab. rms (%):	0.25%
Medium wavelength:	800nm
Bandwidth (FWHM):	30nm

Our theoretical contributions

The group has experience on manipulating atomic transitions with chirped laser pulses.

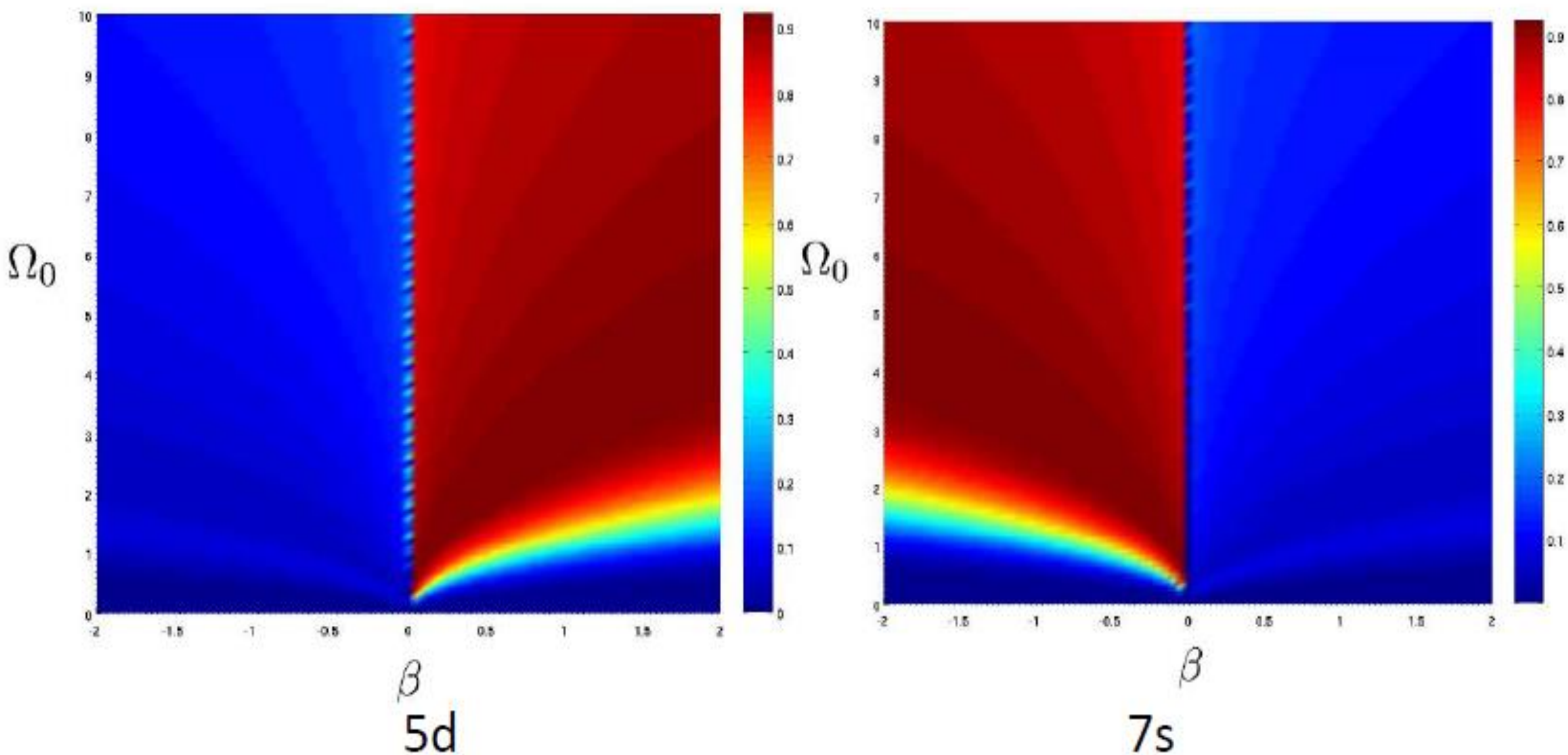
Dynamics of the populations for positive and negative frequency chirp





GP. Djotyan, JS. Bakos, G. Demeter, PN. Ignacz, MA. Kedves, Zs. Sorlei, J. Szigeti, Z.Toth, Phys.Rev A, **68,** 053409 (2003)

Final populations of the excited states 5d and 7s



Proton - Rb collision

- there are some scaling laws available for single ionization in ion-atom collision but only from the ground state

$$\lg\left(\frac{\sigma^{+}}{Z_p}\right) = 3.86 - 0.87\lg\left(\frac{v_p^2}{Z_p}\right)$$

from my Phd

http://geb.uni-giessen.de/geb/volltexte/2003/1036/pdf/BarnaImre-2002-07-03.pdf or
I.F Barna, N. Grün, W. Scheid, Eur. Phys. J.D. 25, 239 (2002)

$$\lg\left(\frac{\sigma^{+}}{Z_p}\right) = 3.63 - 0.78\lg\left(\frac{v_p^2}{Z_p}\right)$$

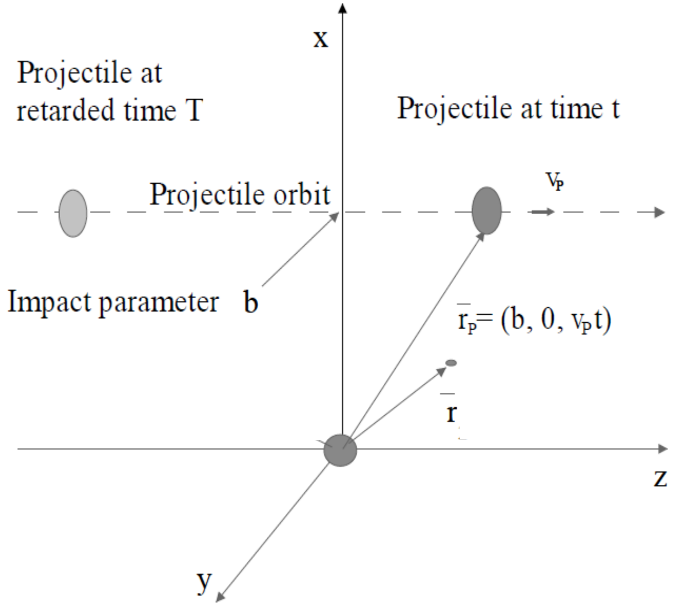
from my colleague:

C. Pfeiffer, N. Grün, W. Scheid, J. Phys. B: At. Mol. Opt. Phys. 79, 3621 (1997)

Proton - Rb collision

-In ion-atom collision the semiclassical approx. is used the projectile is treated classicaly and flies on a straight line

$$\mathbf{R}(t) = \mathbf{b} + \mathbf{v}t, \qquad V = -\frac{Z_A}{|\mathbf{R}(t) + \mathbf{r}|}$$



- the Knudsen parameter describes the external field
  if $Z_{proj}/v_{proj} < 0.1$ perturbative regime, our case 1st Born approx is valid
  matrix element: $V_{\alpha\alpha'} = \langle \varphi_\alpha \mid V(t) \mid \varphi_{\alpha'} \rangle$

  transition amplitude: $a_\alpha(\mathbf{b}) = -i \int_{-\infty}^{+\infty} dt V_{\alpha 0}(t) \exp(i(E_\alpha - E_0)t).$

  Total ionization cross section: $\sigma_{0\to n} = \int d^2\mathbf{b} \mid a_{0\to n} \mid^2$

  Work is in progress

Additional ideas, activity

Very recent result: New exact solutions of the Dirac equation of a charged particle propagating in a strong laser field in an underdense plasma.

EAAC-2013. June 05. La Biodola, IT

1. Introduction, Volkov states, Mathieu charts in medium

2. New exact solutions of the Dirac (K-G) equation

3. Numbers, Numerical examples (Dirac, Klein-Gordon)

[4. Relevance in mechanisms of acceleration in plasma]

[1] S. V. , New exact solutions of the Dirac equation of a charged particle interacting with an electromagnetic plane wave in a medium. Accepted for publication in Laser Physics Letters (2013). E-print: arXiv:1305.4370 [quant-ph]

[2] S. V., A new class of exact solutions of the Klein-Gordon equation of a charged particle interacting with an electromagnetic plane wave in a medium. To be published (2013). E-print: arXiv:1306.0097 [quant-ph]

[3] S. V., New exact solutions of the Dirac equation of a charged particle propagating in a strong laser field in an underdense plasma. 1st European Advanced Accelerator Concepts Workshop, EAAC-2013. June 2-7. La Biodola, IT. Talk on 05. WG1+6

Prof. Varró has analytic solutions for particles in underdense plasma in Dirac/KG Eq.
Mr. Pocsai Msc. Student studies the classical motion of charged particles in underdense plasma

Publications

Conference proceedings:
First European Advanced Accelerator Concepts Workshop

Pre-Excitation Studies for Rubidium-Plasma Generation

M. Aladi, J.S. Bakos, I.F. Barna*, A. Czitrovszky, G.P. Djotyan, P. Dombi, D. Dzsotjan, I.B. Földes, G. Hamar, P. N. Ignácz, M. A. Kedves, A. Kerekes, P. Lévai, I. Márton, A. Nagy, D. Oszetzky, M.A. Pócsai, P. Rácz, B. Ráczkevi, J. Szigeti, Zs. Sörlei, R. Szipőcs, D. Varga, K. Varga-Umbrich, S. Varró, L. Vámos and Gy. Vesztergombi

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Preprint submitted to Nuclear Instruments and Methods in Physics Research A *August 21, 2013*

accepted

or on the Preprint Server:
http://arxiv.org/abs/1309.2442

Additional accelerator coupled activities in Hungary/Wigner

In the planned ELI - ALPS superlaser at Szeged we plan to accelerate electrons and protons with short laser pulses

accelerated protons planned to be used for hadron therapy

On Zimányi 2012 last year we had a bit more detailed talk:
Particle accelarator at the ELI ALPS
https://indico.cern.ch/conferenceOtherViews.py?confId=218974

Thank you for your attention!