Project Review: Status of AWAKE Project

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AWAKE Group

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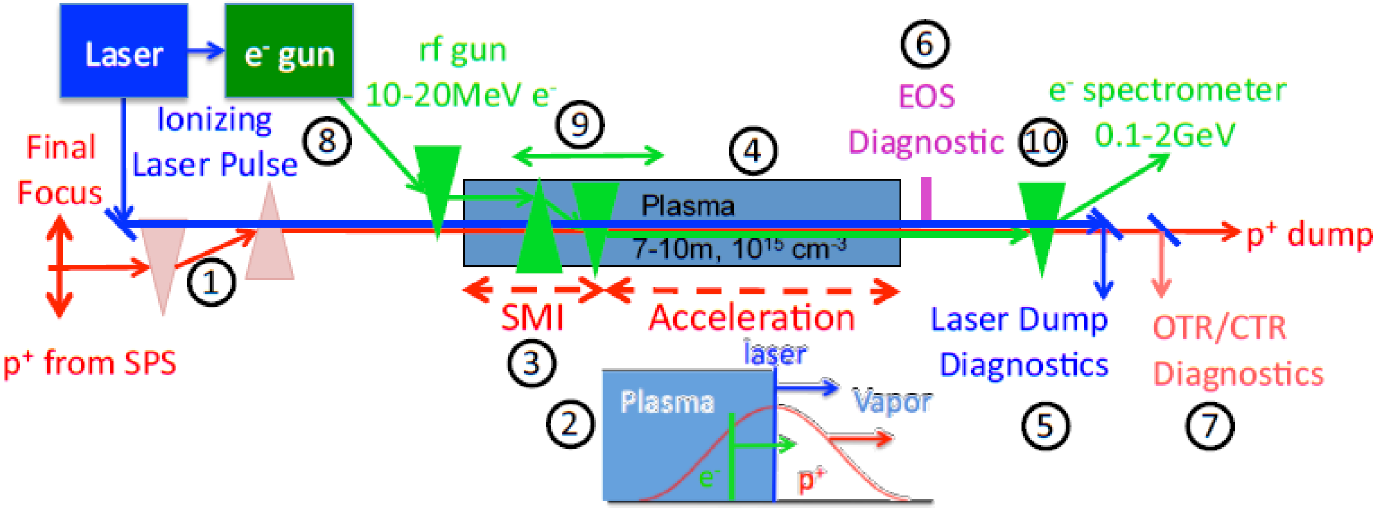
What is AWAKE?

- AWAKE stands for Advanced WAKefield Experiment.
- 400 GeV proton beam drives wakefields in a 10 meter plasma through a self modulation instability
- The wakefields accelerate electrons from 16 MeV to 2 GeV

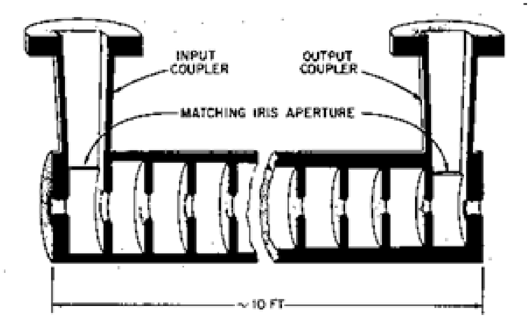
Experiment organized into three phases:

- Phase I: Demonstration of self-modulation instability
- Phase II: Electron acceleration over 10 m
- Phase III: Electron acceleration over long distances (yet to be approved)

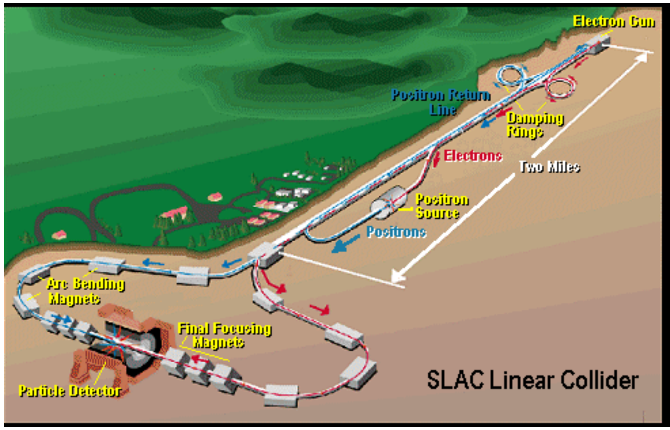


Why Advanced Accelerators?

- Traditional RF (cm) scale accelerators
  - Accelerating gradient limited to 50-100 MeV/m (state of the art limit) due to breakdown of the walls
  - High energy accelerators must be larger and therefore costly
- Advanced Accelerators:
  - High Gradients
  - Shorter distance for same energy
  - Can have lower costs for higher energy designs
- Traditional accelerator and collider designs will become prohibitively costly at higher energies

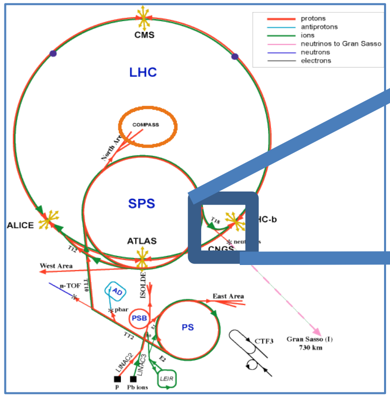


SLAC Accelerating Section (TW)

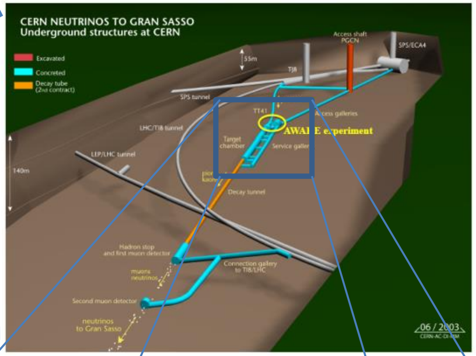


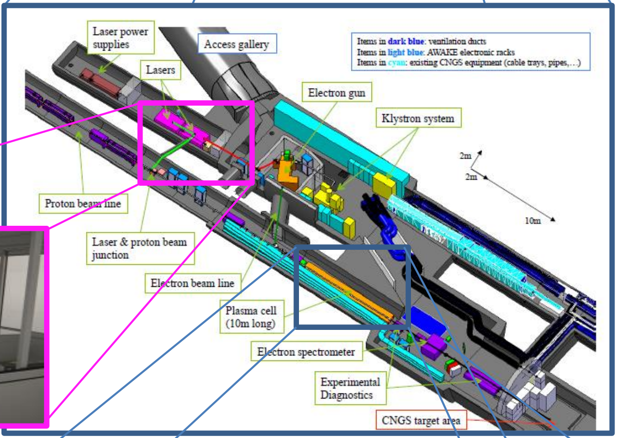
50 GeV electrons in 3.2km
16 MeV/m gradient

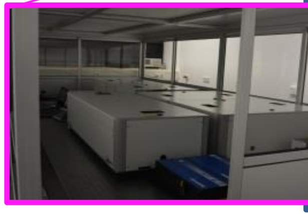
AWAKE at CERN



SPS Scale





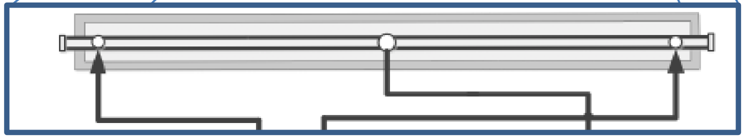


MPP Laser

AWAKE Scale

Diagnostics:

- OTR/CTR proton beam diagnostics
- Electron Spectrometer



10 m Rb vapor source

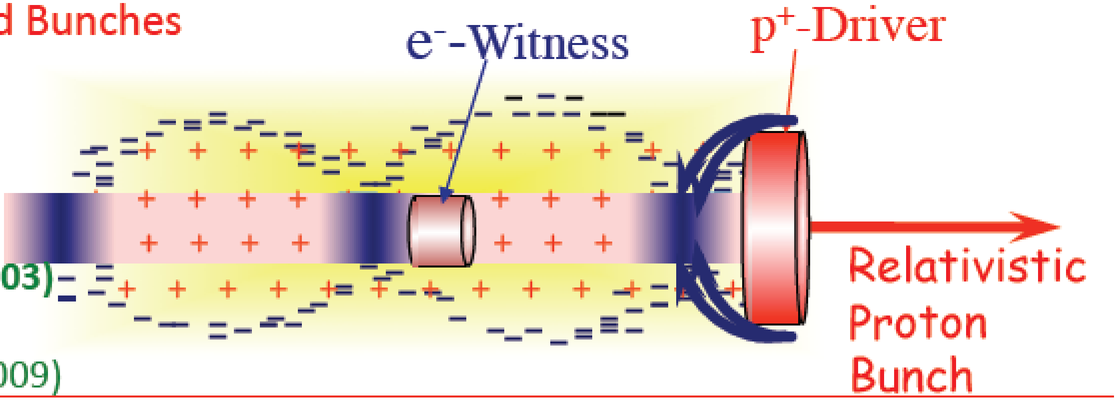
What is Plasma Wakefield Acceleration?

- Fields from the relativistic charged particle beam drives wakefields in the plasma
- Electrons can be trapped within the wakefield's accelerating and focusing phase and produce a high quality electron beam in a short distance

$$E_{z,linear} \propto \frac{N}{\sigma_z^2}$$

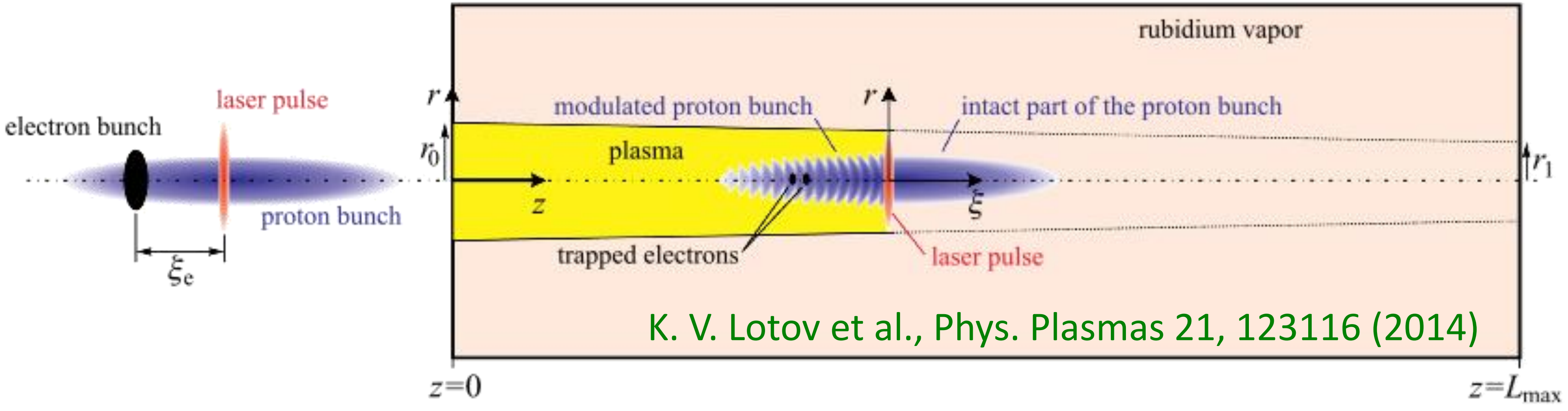
E_z: accelerating field,
N: # particles/bunch
σ_z: gaussian bunch length,

Positively Charged Bunches



Blue, et al.
PRL, 90, 214801 (2003)
Caldwell, et al.
Nat. Phys. 5, 363 (2009)

The AWAKE Experiment



K. V. Lotov et al., Phys. Plasmas 21, 123116 (2014)

FIG. 1. Geometry of the problem (not to scale). The beams are shown at two times.

Plasma requirements:

✧L~10m	~$\beta^*_{protons}$
✧n_e=1-10x10^{15}cm^{-3}	$k_{pe}\sigma^*_r$<1
✧$\Delta n_e/n_e$~0.2%	Inject ~100λ_{pe}~$\sigma_{z,\ protons}$
✧r~1mm	~c/ω_{pe}
✧Heavy ions	use ~100ω_{pe}^{-1}

✧Laser ionization provides seeding for the SMI

Using Protons

Parameter & notation	Value
Plasma density, n_e	$7 \times 10^{14}\,\mathrm{cm}^{-3}$
Plasma ion-to-electron mass ratio (rubidium), M_i	157 000
Proton bunch population, N_b	3×10^{11}
Proton bunch length, σ_z	12 cm
Proton bunch radius, σ_r	0.02 cm
Proton energy, W_b	400 GeV
Proton bunch relative energy spread, $\delta W_b / W_b$	0.35%
Proton bunch normalized emittance, ϵ_{bn}	3.5 mm mrad
Electron bunch population, N_e	1.25×10^9
Electron bunch length, σ_{ze}	0.25 cm
Electron bunch radius at injection point, σ_{re}	0.02 cm
Electron energy, W_e	16 MeV
Electron bunch normalized emittance, ϵ_{en}	2 mm mrad
Injection angle for electron beam, ϕ	9 mrad
Injection delay relative to the laser pulse, ξ_0	13.6 cm
Intersection of beam trajectories, z_0	3.9 m

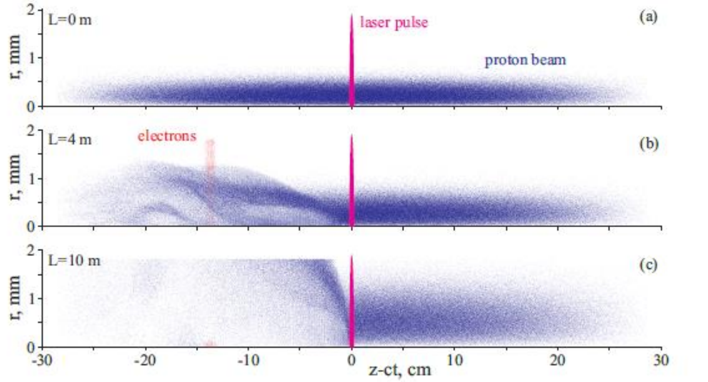


Fig. 5: Distribution of the beams at (a) the entrance to the plasma, (b) after propagating 4 m in the plasma, and at (c) the exit from the plasma cell. Protons are blue, electrons are red and the laser pulse is the line at $z - ct = 0$. The laser pulse seeds the SMI for the proton bunch.

- Protons can potentially propagate through long plasmas without reaching depletion
- With a plasma wavelength of ~1mm, and a proton beam ~12cm, we rely on the self modulation instability to drive the wakefields

Contributions of the Institute

- Vapor Source
  - Vapor source: Provides uniform Rb vapor
  - Rb Vapor Diagnostic
- TW Power Laser:
  - Ionizes Rb to make plasma and seeds self modulation,
  - Seed for photocathode drive to make electron beam in phase II
  - Ablation Studies for Beam Dump
- Diagnostics
  - OTR: Streak camera to determine proton modulation
  - CTR: Coherent transition radiation to determine proton modulation
  - Shadowgraphy (Transverse plasma diagnostic for ends)
- Material Support
  - Design and Fabrication
  - Financial

Plasma Source

- Density adjustable from **10^{14} – 10^{15} cm^{-3}**
- 10 m long, 4 cm diameter

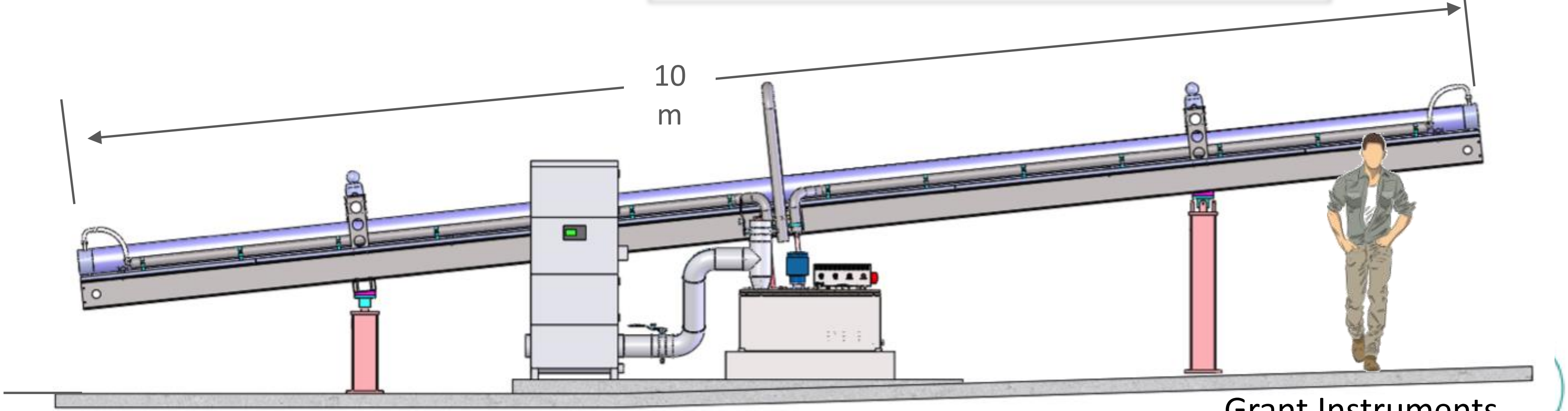
- Plasma formed by field ionization of Rb
  - Ionization potential Φ_{Rb} = 4.177eV
  - above intensity threshold (I_{ioniz} = 1.7 x 10^{12}W/cm^2) 100% is ionized.

- Plasma density = vapor density

- System is oil-heated ~ 200˚ C
  - → keep temperature uniformity
  - → Keep density uniformity

(2) 10m heat exchangers @ CERN

E. Öz, P. Muggli, NIM 740 (2014) 197.

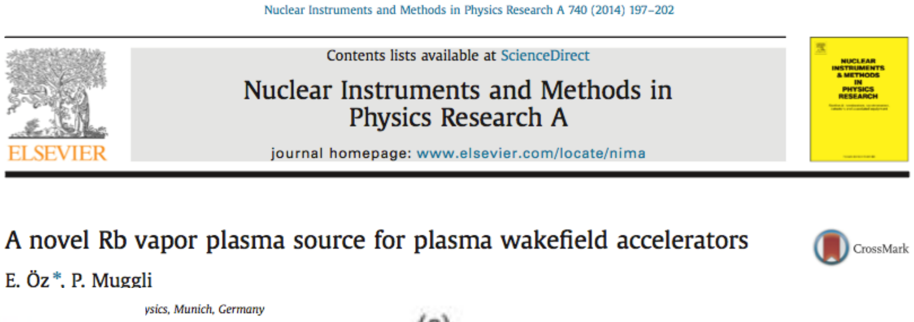


Grant Instruments

Vapor Source

<u>People Involved:</u>

- P. Muggli
- E. Oz
- F. Batsch
- N. Savard



Nuclear Instruments and Methods in Physics Research A 740 (2014) 197–202

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A novel Rb vapor plasma source for plasma wakefield accelerators

E. Öz*, P. Muggli

ysics, Munich, Germany

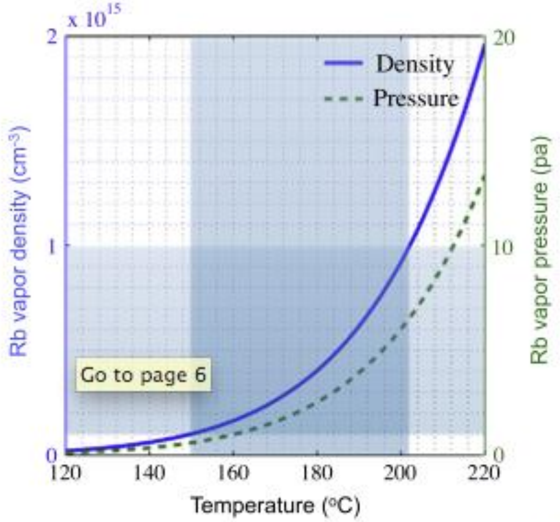


Fig. 1. Rubidium vapor density (blue line) and vapor pressure (green dashed line) as a function of temperature. Region between 1×10^{14} cm^{-3} and 1×10^{15} cm^{-3}, and the corresponding temperature show the parameter range of interest for the PDPWFA. (For interpretation of the references to color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

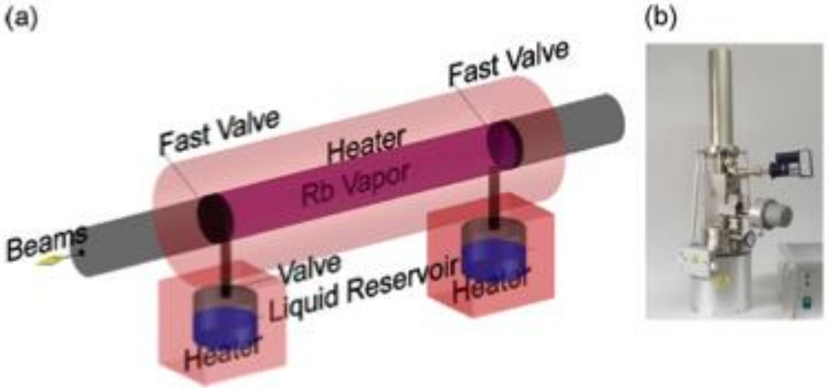


Fig. 2. (a) Sketch of the plasma source. Two independently heated sections consist of a 10 m long Rb vapor section with fast valves for proton, electron and laser beam access and valved Rb liquid reservoirs. (b) Photo of the valved Rb liquid reservoir by MBE Komponenten incorporated.

Rubidium: ^{85}Rb(72%)+^{87}Rb(28%) ϕ_i=4.22eV I_{thresh}~1.7x10^{12} Wcm^{-2} T_{melt}=39°C

Rb vapor with imposed temperature (150-220°C) Laser pulse ionized (100fs, ~100mJ, w_0=1mm)

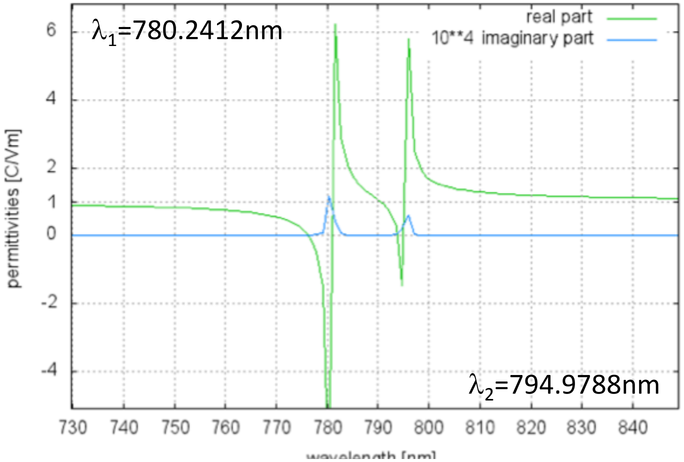
Rb Vapor Density Measurements

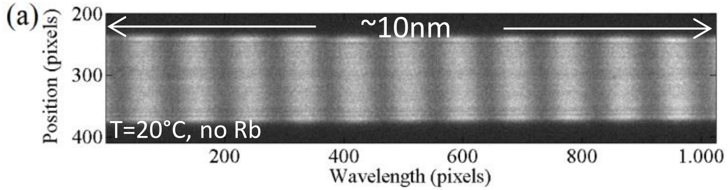
$$\epsilon'(\lambda) = 1 + \frac{e^2 N_i}{\epsilon_0 m_e} \sum_{j \neq i} \frac{f_{ij}\left(\frac{1}{\lambda_{ij}^2} - \frac{1}{\lambda^2}\right)}{\left(\frac{2\pi c}{\lambda_{ij}^2} - \frac{2\pi c}{\lambda^2}\right)^2 + \gamma_{ij}^2 \frac{1}{\lambda^2}}$$

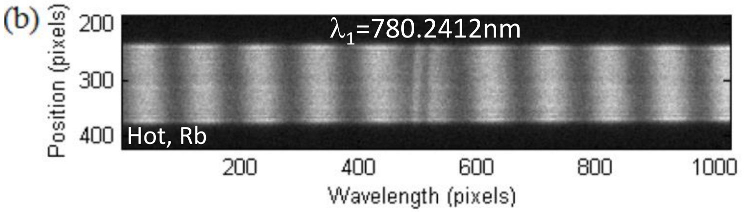
=>Dispersion (anomalous)

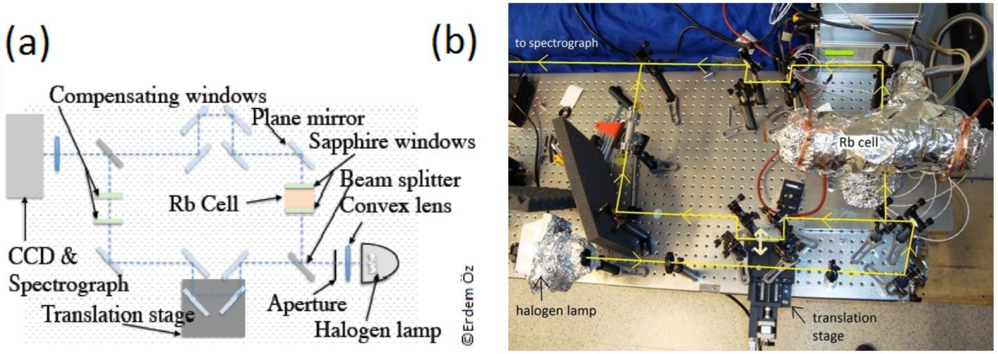
$$\epsilon''(\lambda) = \frac{e^2 N_i}{\epsilon_0 m_e} \sum_{j \neq i} \frac{f_{ij}\gamma_{ij}\frac{2\pi c}{\lambda}}{\left(\left(\frac{2\pi c}{\lambda_{ij}}\right)^2 - \left(\frac{2\pi c}{\lambda}\right)^2\right)^2 + \gamma_{ij}^2\left(\frac{2\pi c}{\lambda}\right)^2}$$

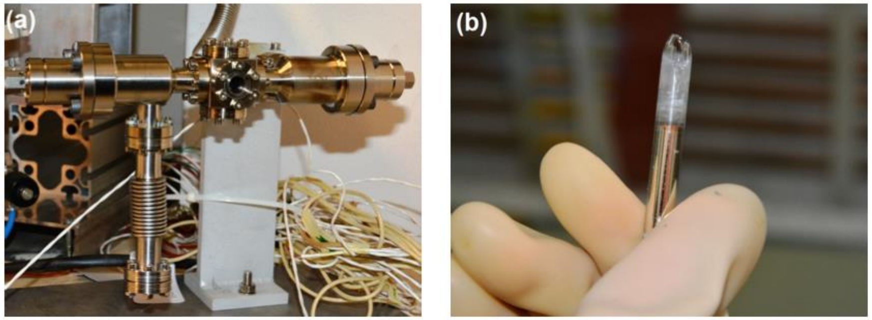
=>Absorption

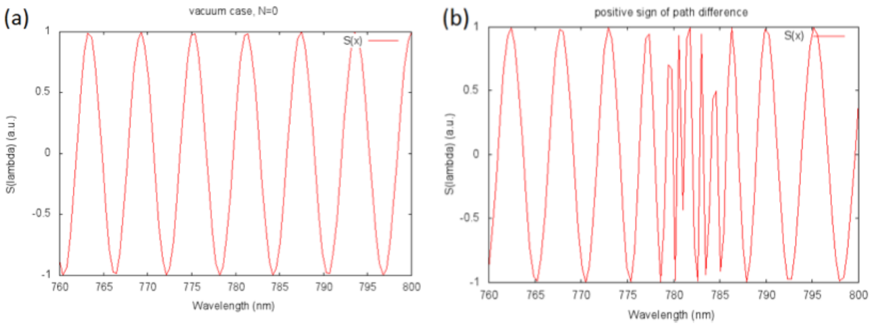






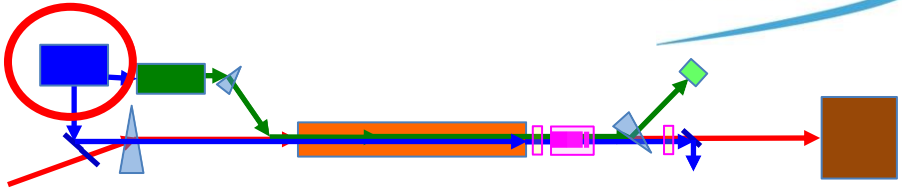




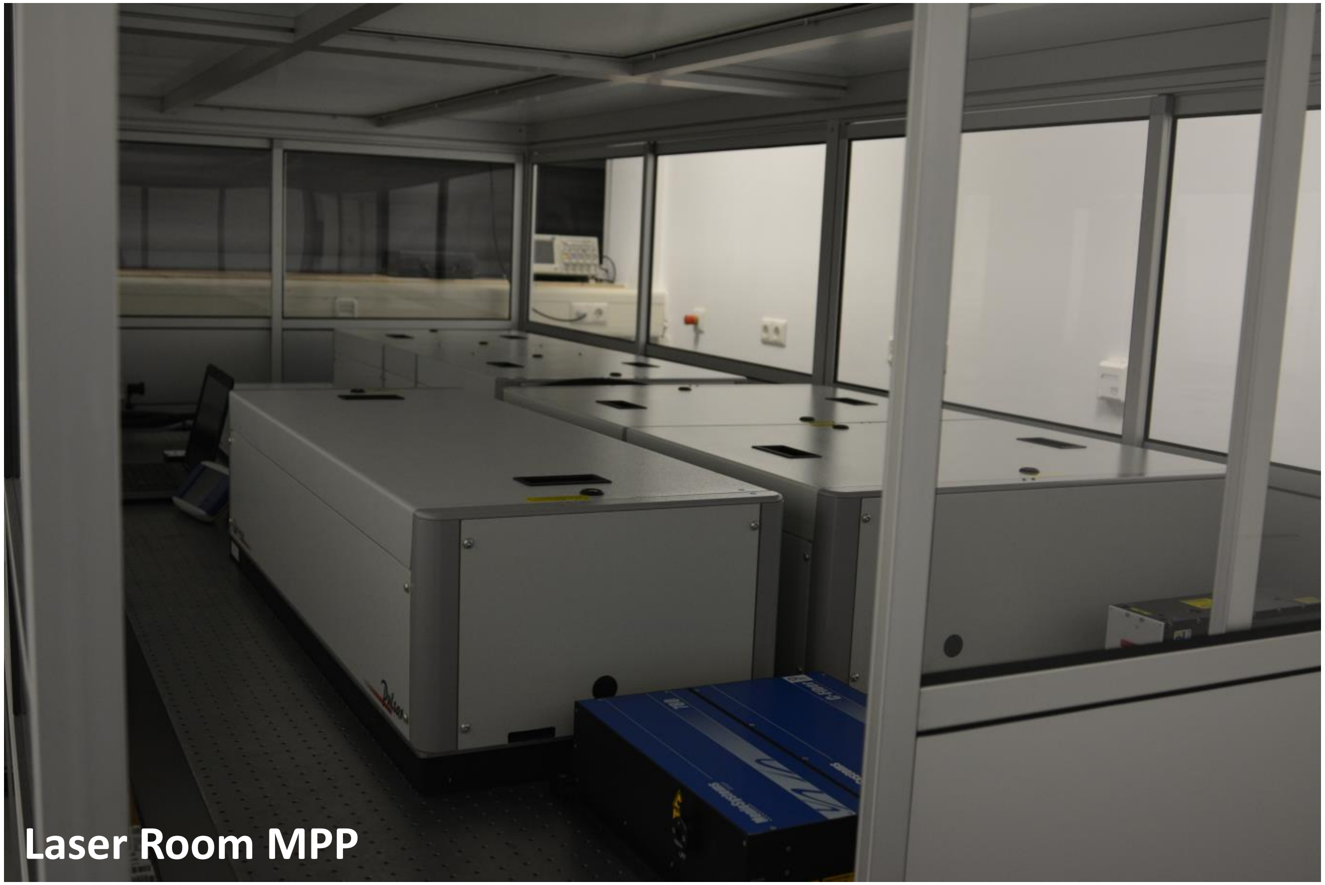


- ✧ Measured AWAKE density range ($10^{14} < n_{e0} < 10^{15}$cm^{-3}) in the expected temperature range (180-200°C), Bachelor Thesis, F. Batch, TUM, 2014
- ✧ Diagnostic to be implemented in AWAKE (Master Thesis …)

TW LASER



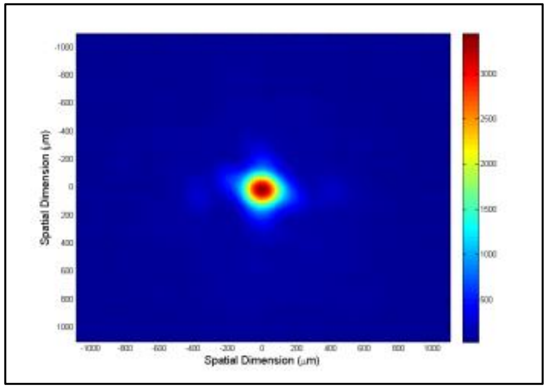

Laser Room in AWAKE area


Laser Room MPP

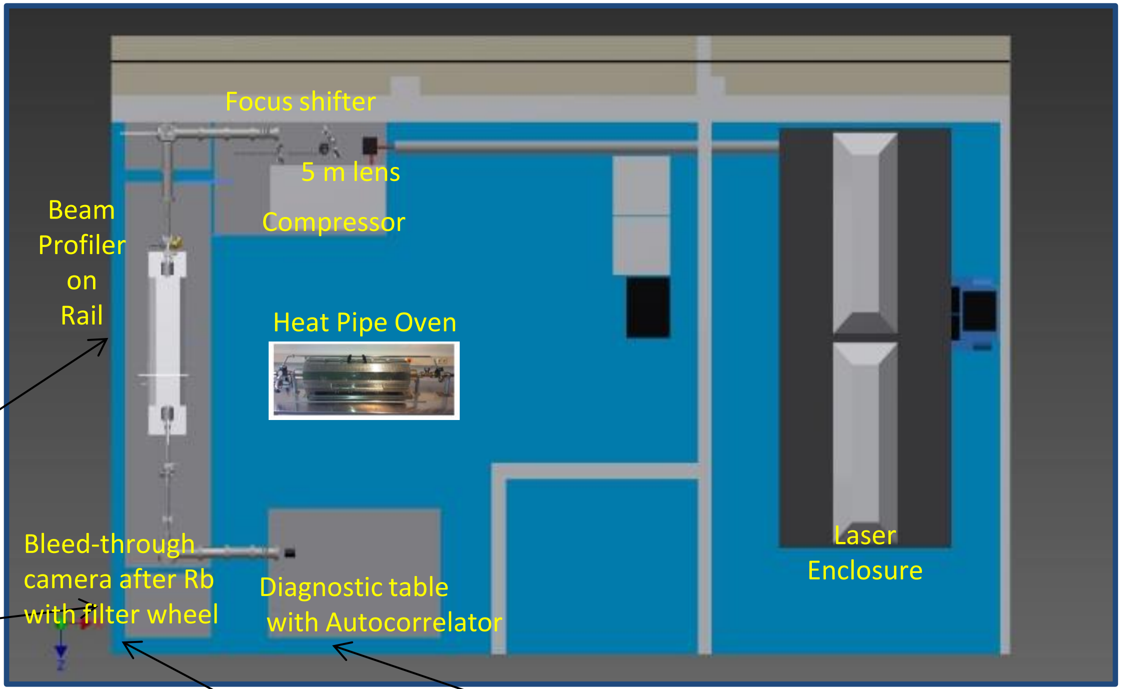
Laser Beam	
Laser type	Fiber Ti:Sapphire
Pulse wavelength	λ_0 = 780 nm
Pulse length	100-120 fs
Pulse energy (after compr.)	**450 mJ**
Laser power	**4.5 TW**
Focused laser size	**$\sigma_{x,y}$ = 1 mm**
Rayleigh length Z_R	3 m
Energy stability	±1.5% r.m.s.
Repetition rate	10 Hz

Laser installed & operating at MPP since fall 2014. Will move to CERN early 2016.

TW LASER at the Institute



Spot at center first heater,
w0 radius is 200 um



Focus shifter

5 m lens

Beam
Profiler
on
Rail

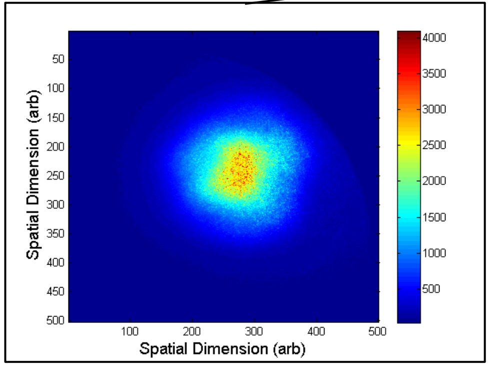
Compressor

Heat Pipe Oven

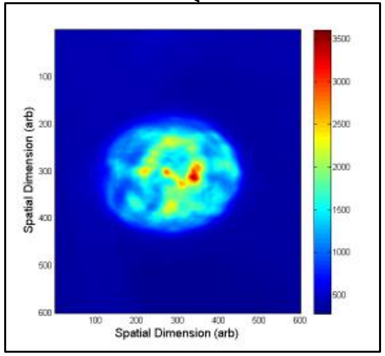
Bleed-through
camera after Rb
with filter wheel

Diagnostic table
with Autocorrelator

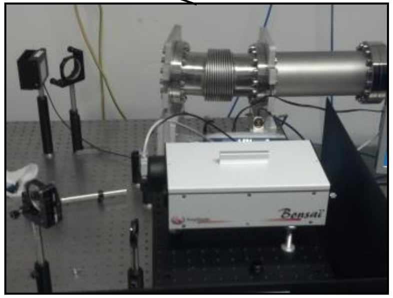
Laser
Enclosure



100uJ Pulse No Rb



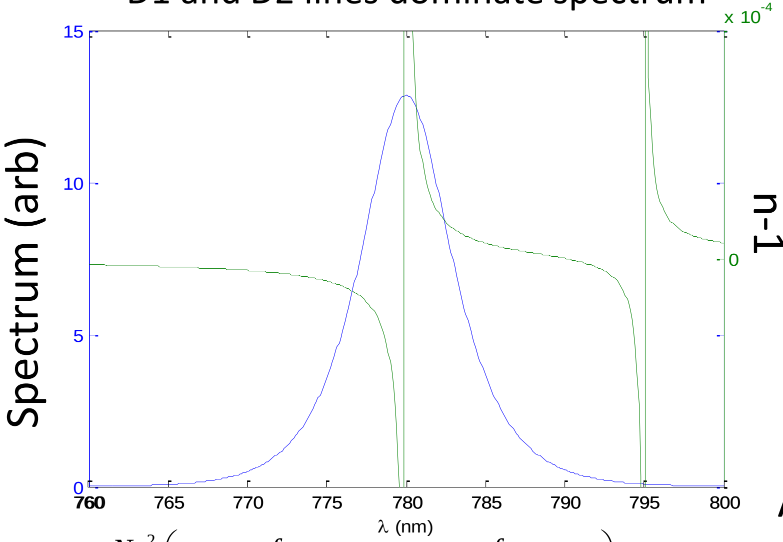
10mJ Pulse Power with Rb



SHG Intensity AutoCorrelator

LASER at the Institute:
Laser Propagation

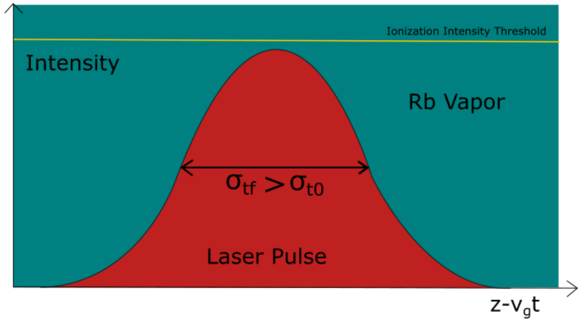
D1 and D2 lines dominate spectrum



$$\chi_{bound} = \frac{Ne^2}{m\varepsilon_0}\left(\frac{f_1}{\omega_{01}^2 - \omega^2 - i\Gamma_1\omega} + \frac{f_2}{\omega_{02}^2 - \omega^2 - i\Gamma_2\omega}\right)$$

At Intensities much less than ionization:

- Differential index across BW of laser ~10^{-4}
- Laser pulse is stretched on cm scale

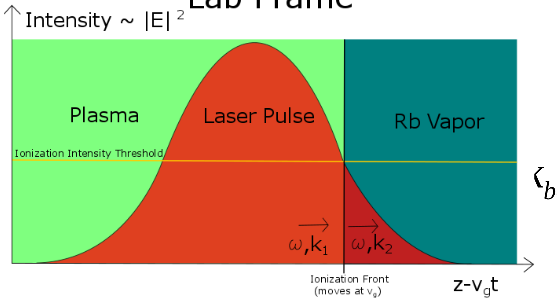


At Intensities **above** ionization:

- Leading edge of the pulse ionizes or saturates the transition
- Most of the pulse travels through plasma, samples plasma dispersion, which has a differential index on the scale of 10^{-8}

$$k_{plasma} = \frac{\omega}{c}\sqrt{1-\frac{\omega_p^2}{\omega^2}}$$

Lab Frame



$$k_{bound} = \frac{\omega}{c}\sqrt{1+\chi(\omega)}$$

Pulse stretching will lower peak intensity, causing drop below ionization threshold BUT for intensities at AWAKE (>2 TW/cm²):

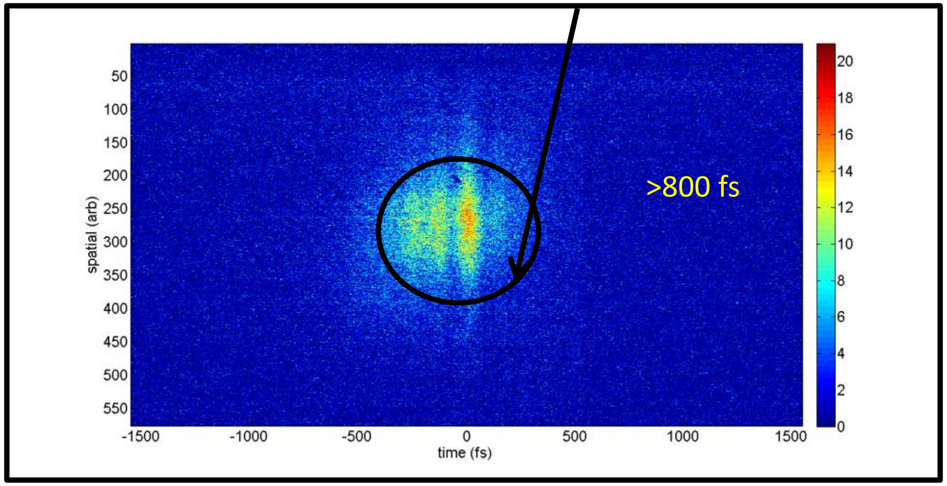
We expect little pulse stretching of most of pulse

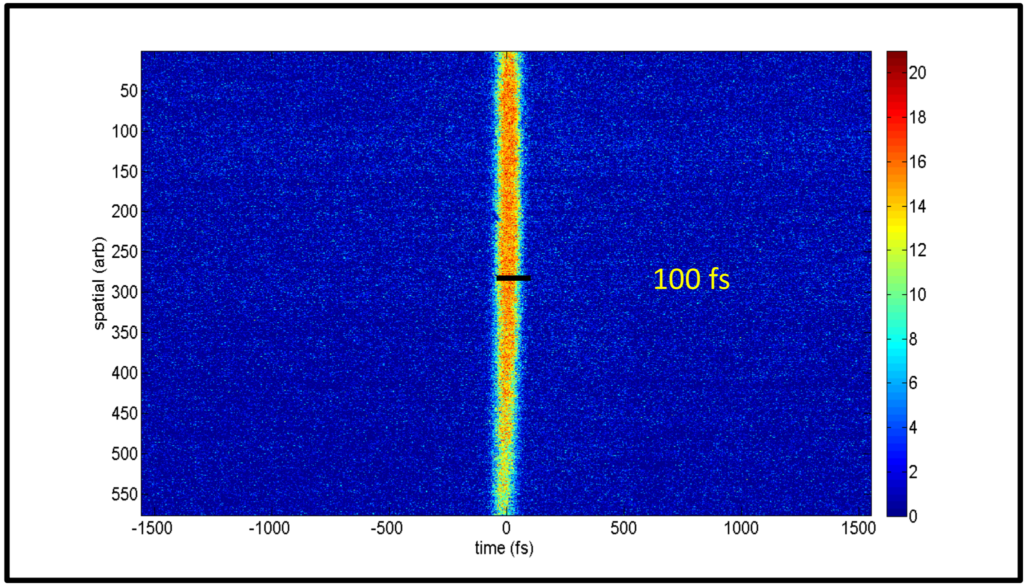
Measurement with 25 cm Rb in Heatpipe Oven

Laser Intensity through plasma ~100 MW/cm^2

Large scale broadening observed: from 100 fs to > 800 fs.

Spot size is set by aperture



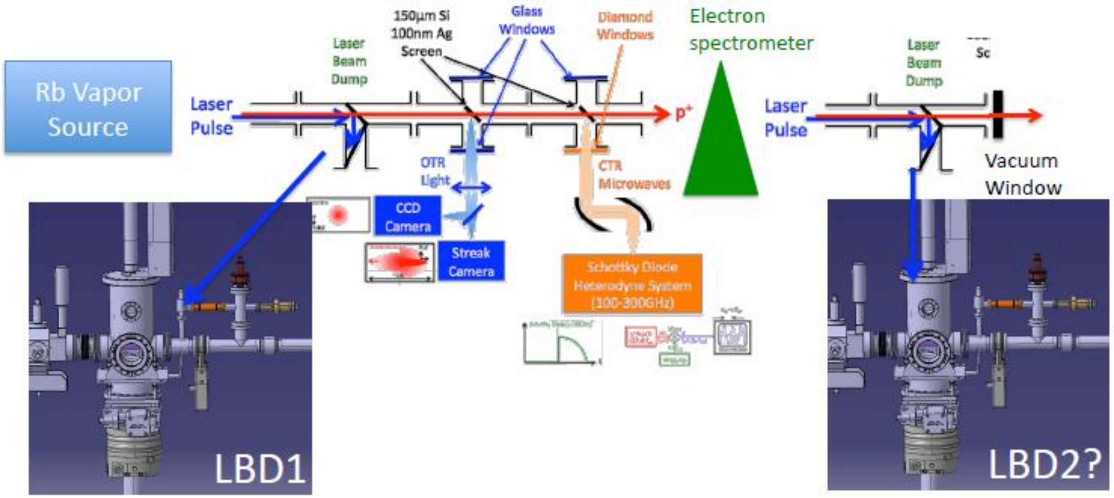


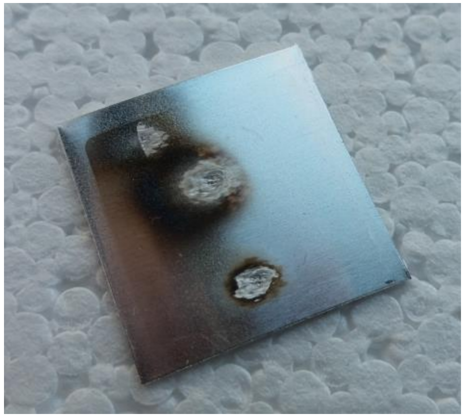
Autocorrelation image with focusing

Laser Intensity through plasma ~1 TW/cm^2

NO PULSE BROADENING OBSERVED!!! "PURPLE LIGHT" OBSERVED OUT OF BLEED PORT

LASER at the Institute: Ablation Study for Laser Dump





Laser Ablation Foil at MPP

- Laser Dump protects proton diagnostic screen from laser damage.
- Dump is a foil on a translation stage that is moved before breakthrough
- Foil should be thin to minimize radiation and thick enough such that we won't have to change the foil in a run period (two weeks)
- AWAKE fluence used to impact foils of different materials and thicknesses and the number of shots measured at MPP Laser lab.

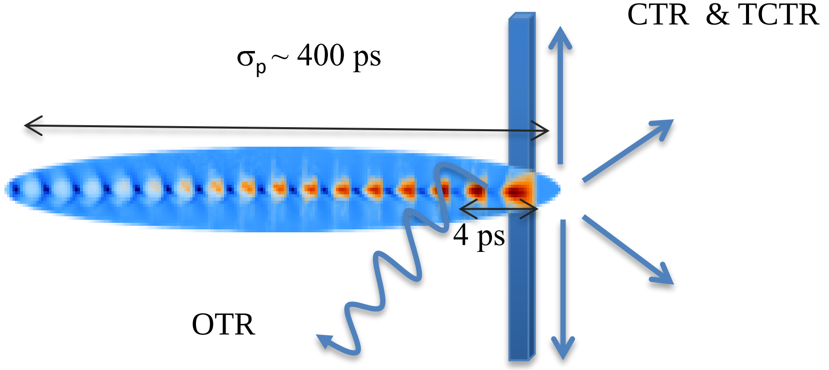
Proton Modulation Diagnostics for Phase I: OTR / CTR

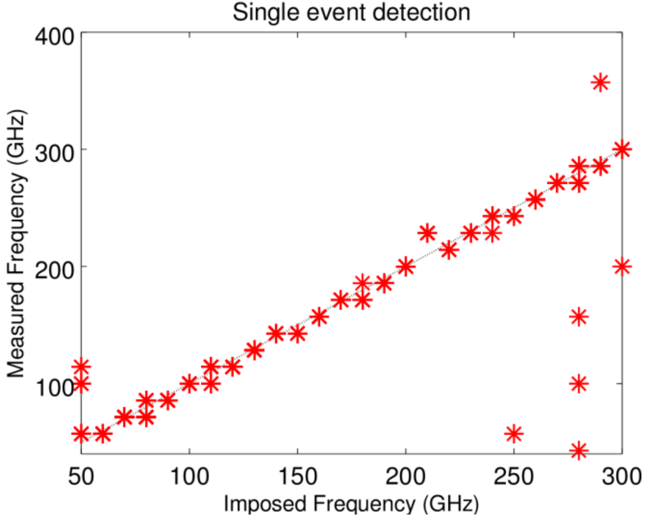
Measure radiation emitted by the bunch when traversing a dielectric interface

Optical Transition Radiation → streak-camera

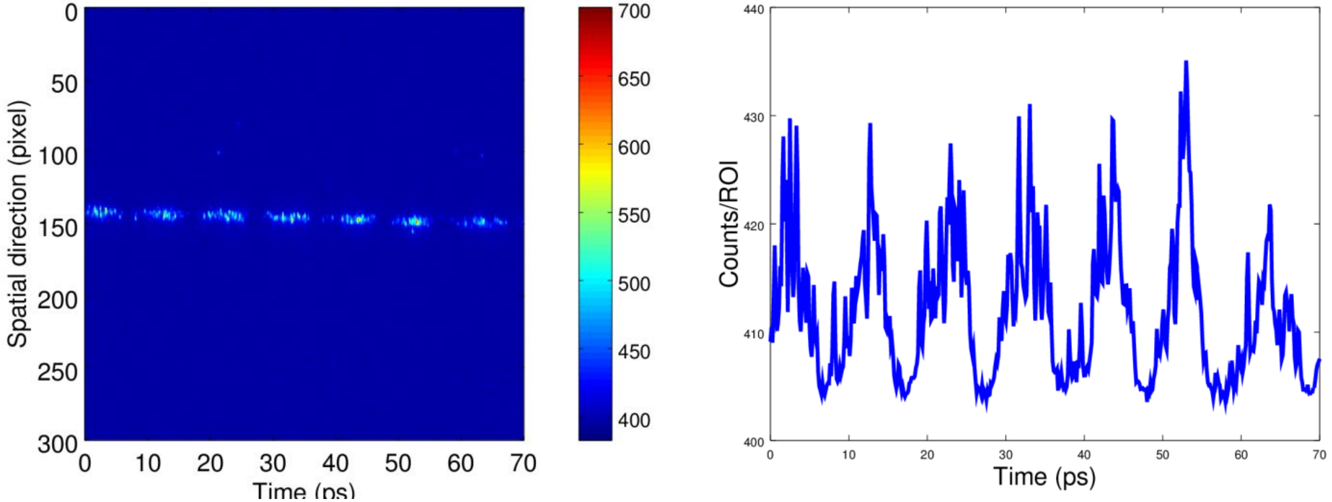
Coherent Transition Radiation → variety of techniques under evaluation

Will work single shot !





Simulated 100 GHz OTR signal in lab @ MPP



Summary

AWAKE is a plasma wakefield acceleration experiment at CERN.

MPP Contributions
Vapor Source and density diagnostics
Ionization / electron photocathode Laser
Phase I proton modulation diagnostics

Schedule
Laser will move from MPP to CERN in second week of January
Installation of Diagnostics will occur in January / Februrary
Phase I experiment will begin in Q4 of 2016

Watch for first experimental SMI results in Q4 2016!!!

Group Members and Acknowledgements

- Group members
  - Director : Allen Caldwell
  - Group Leader : Patric Muggli
  - Postdocs:
    - Mikhail Martynaov : Diagnostics, CTR
    - Joshua Moody : Laser propagation / ionization experiment
    - Erdem Öz : Vapor source development
  - Students:
    - Anna-Maria Bachmann : Shadowgraphy
    - Fabian Batsch: Vapor source density diagnostic
    - Mathias Hünther: Laser dump ablation
    - Atefeh Joulaei: Laser propagation/ ionization modelling
    - Nicholas Savard : Vapor source development
    - Karl Rieger: Diagnostics, OTR

- Special Thanks:
  - Machine shop
  - Mister Finenko
  - Mister Haubold