First experimental results towards demonstrating the self-modulation instability at PITZ.

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Abstract

The self-modulation instability is a plasma-particle beam interaction, where a long (with respect to the plasma wavelength) particle beam is separated into bunchlets. The bunchlets, which are about a plasma wavelength long, are generated when a steplike disturbance (e.g. co-moving ionization front, or sharp rise of the particle beam density) excites a plasma wave. The self-modulation is a key element in the design of the plasma acceleration experiment by the AWAKE collaboration at CERN, which is due to start operation later this year. To study this instability in detail an experiment was conceptualized at the Photo-Injector Test Facility at DESY, Zeuthen site (PITZ), to inject a 6 mm long electron beam into a lithium plasma with a density of 10^{15} cm^{-3}. Here we report about first experiments with a novel cross-shaped plasma cell which was inserted into the PITZ beam line. The lithium plasma cell is prepared with argon buffer gas, then heated up to 700°C to achieve a lithium atmosphere with the necessary density. The lithium is ionized with an ArF laser (193 nm wavelength) via sideports, creating a plasma channel with a length of up to 10 cm. The 22 MeV electron beam available at PITZ is focused tightly into the plasma, then guided from there to the diagnostics elements.

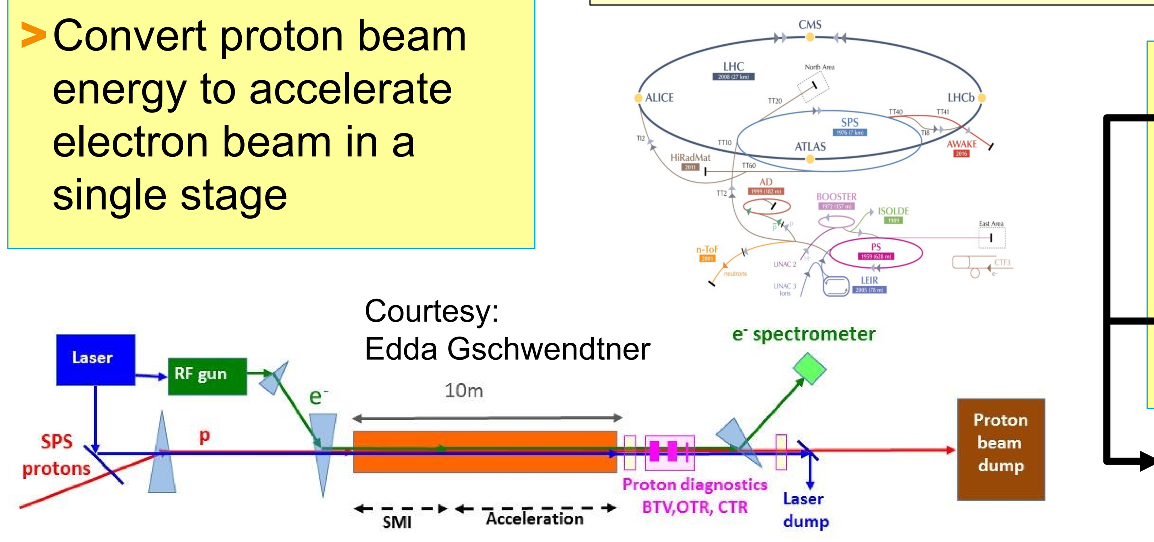
Motivation: A Proton-Driven Plasma Wakefield Experiment at CERN (AWAKE) needs self-modulation

> Use high energy proton beams from SPS to drive plasma wave

> Convert proton beam energy to accelerate electron beam in a single stage

Caldwell et al., Nature Physics (2009):

$$E_{z,max} = 240(MV\,m^{-1})\left(\frac{N}{4x10^{10}}\right)\left(\frac{0.6}{\sigma_z(mm)}\right)^2$$



Courtesy: Edda Gschwendtner

> High accelerating gradient requires **short** bunches (σ_z less than 100µm)

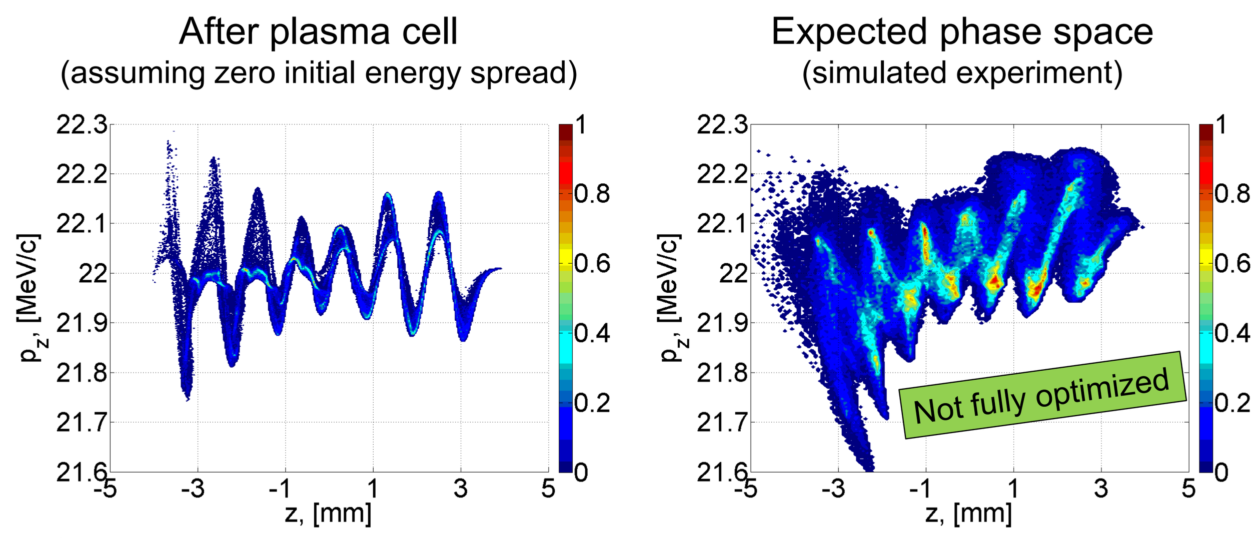
> Existing proton machines produce **long** bunches (10cm)

Self-modulation

Detailed study at PITZ

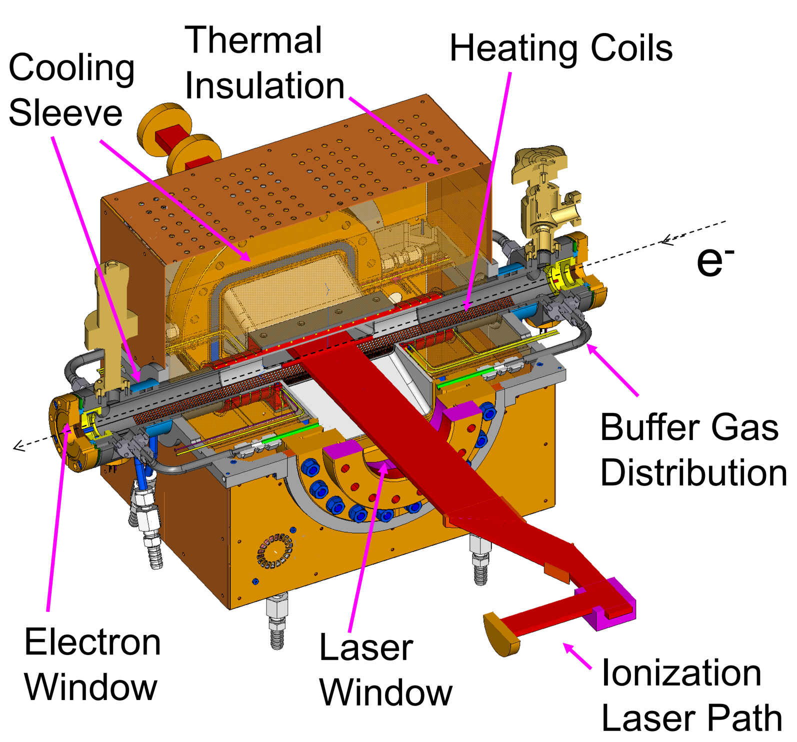
Self-modulation at PITZ

Longitudinal phase-space studies



Experiment is feasible → a plasma cell is needed

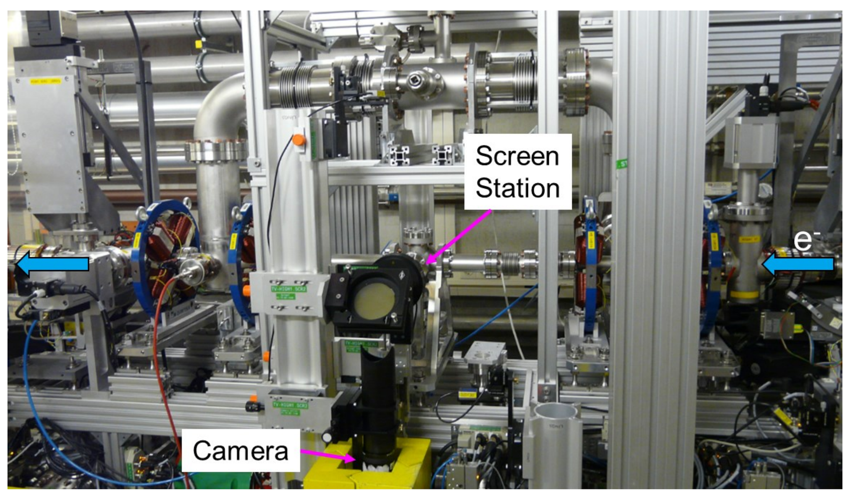
Plasma cell design: novel cross shape



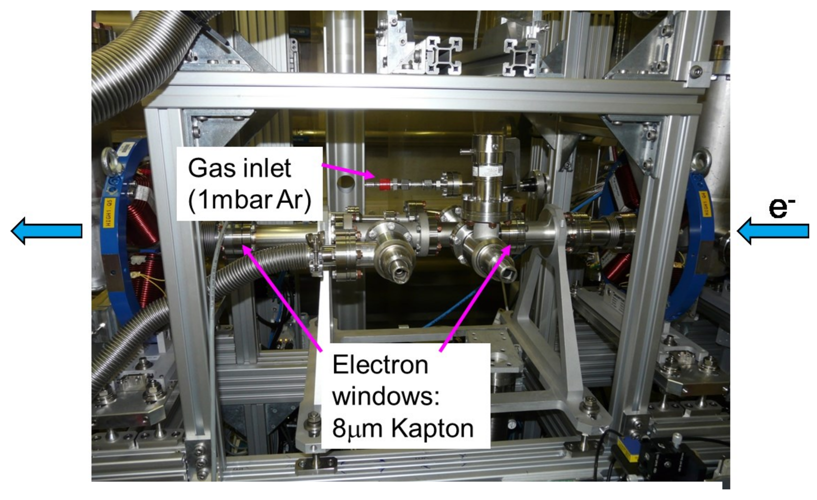
> Novel design saves space and has several advantages compared to simple heat pipe oven:
> - Length of plasma channel is well defined by width of ionization laser beam and can be further adjusted with apertures
> - Arbitrarily defined plasma density profile can be realized with absorption filter mask
> - Side ports can be utilized for plasma diagnostics

Pre-experiments at PITZ: measurement of critical parameters

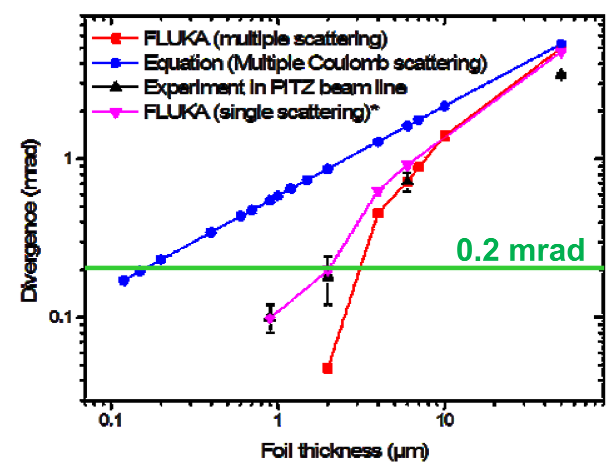
> Pre-experiment #1: Screen station
- Purpose: find quadrupole settings for best focusing
- Setup: screen station at dedicated plasma cell position
- Result: ≈100µm spot size (100 pC bunch charge; 22 MeV; no window foil)



> Pre-experiment #2: Dummy plasma cell
- Purpose: test of interaction of electron beam with electron window foils
- Necessity: machine safety → need to check influence of heating by electron beam / dark current and radiation
- Setup: pipe filled with buffer gas at nominal pressure at dedicated plasma cell position – sealed to beam vacuum with electron windows to be tested
- Result: no damage after several hours of continuous run (nominal conditions and factor 100 more); negligible gas diffusion

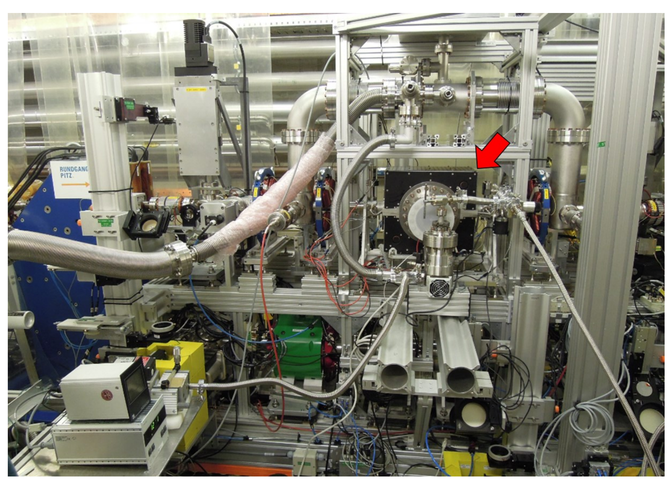


> Pre-experiment #3: Electron beam scattering
- Purpose: find maximal allowable polymer window foil thickness
- Necessity: low energy (22 MeV) electron beam is strongly scattered by window foils
- Setup: foil inserted into electron beam path – measurement of beam size after drift space – comparison with size without scattering
- Result: foil thickness has to be <2µm to cause beam divergence of <0.2 mrad (maximal allowable value according to beam dynamics simulations)

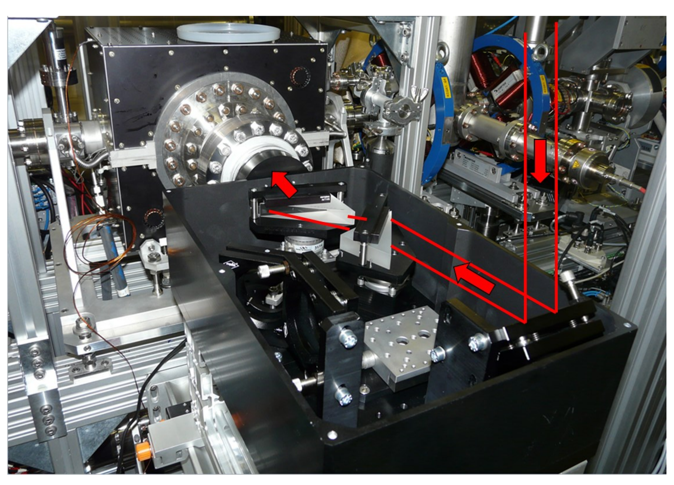


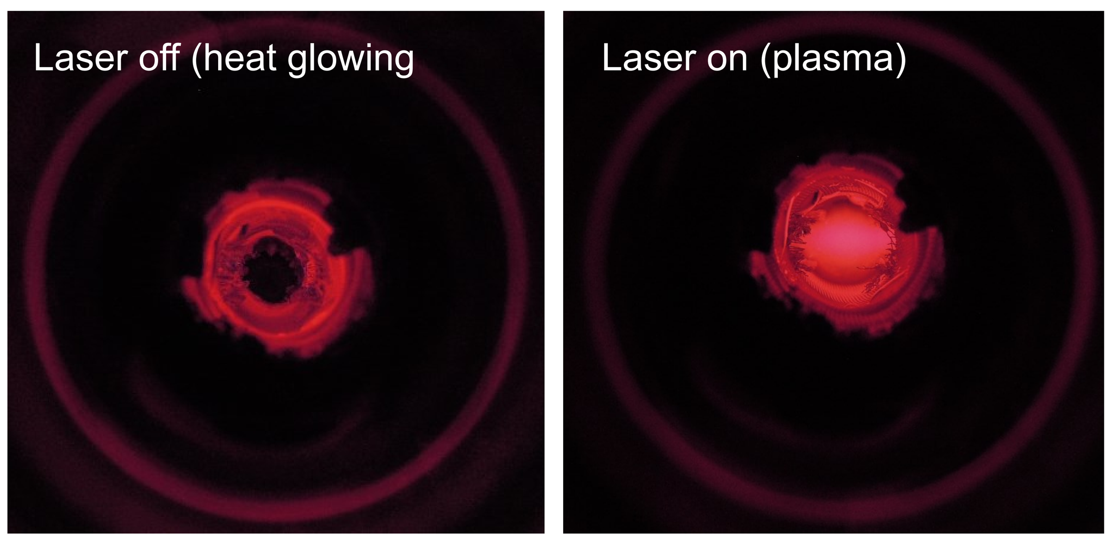
Initial self-modulation experiments

Plasma cell installed in PITZ beam line



Plasma cell with ionization laser beam expander





> **First plasma in a cross shaped heat pipe oven worldwide!**

> Experiments in 2015: two runs with ≈200 hours of operation in total

> Looking for self-modulation signature:
- Spatial modulation → Observation of electron beam on screen station after plasma cell
- Energy modulation → Observation of beam momentum with dipole spectrometer after plasma cell
- Phase space modulation → Observation of longitudinal phase space with RF deflector / spectrometer

> Result: No self-modulation seen - this was caused by several factors:
- Low gas density (1/100 → due to deficient heating power / insufficient lithium circulation)
- Low ionization laser pulse energy into plasma cell (1/10 → due to lossy laser beam transport)
- Strong electron beam scattering at the window foils (8 µm Kapton windows were used)

Outlook

Problems	Solutions
Heating wires overpowered	Stronger heater / better heat insulation
Lithium accumulation in cooling zones	• Finer mesh → better lithium transport • Longer side arms
Only 10% laser pulse energy delivered to plasma cell	• Better optics (e.g. cylinder lenses; antireflection coating) • Increase efficiency of laser transport (less atmospheric absorption)
Electron windows increase achievable focus size	Thinner electron window foils

> **Good chance for successful plasma experiments in 2016 with improved hardware**

PITZ Photo Injector Test Facility Zeuthen

HELMHOLTZ ASSOCIATION