

# Studies for Particle Driven Plasma Acceleration at PITZ

Experiments planned utilizing PITZ (Photo Injector Test facility at DESY, Zeuthen site)

Matthias Gross  
Grömitz,  
21. March 2013

# Background

**Background:** Proton-driven PWFA experiment proposed at CERN:

- Use high energy proton beams to drive wake (plasma wave)
- Convert proton beam energy into  $e^-$  or  $e^+$  beam in a **single** stage



Courtesy of  
Carl Schröder,  
LBNL

Caldwell *et al.*, *Nature Physics* (2009); Lotov, *PRST-AB* (2010)

⇒ high gradient requires high density:  $E_z \propto n^{1/2}$

⇒ large wake requires resonance beam:  $L_b \sim \lambda_p \propto n^{-1/2}$

$$E_{z,\max} \approx 3 \text{ GV/m} \left( \frac{N_b}{10^{10}} \right) \left( \frac{100 \mu\text{m}}{\sigma_z} \right)^2 \ln(\sigma_z/\sigma_r)$$

⇒ high accelerating gradient requires **short** bunches  $\sigma_z \lesssim 100 \mu\text{m}$

⇒ existing proton machines produce **long** bunches  $\sigma_z \sim 10 \text{ cm}$

- Use beam-plasma instability to modulated the beam at  $\lambda_p$ , driving large plasma waves for acceleration *Kumar et al.*, *PRL* (2010); Lotov, *Phys. Plasmas* (2011)

**Does this work ?**  
→ Dephasing ?  
→ Hose instability ?



# Why Experiments at PITZ?

## > Favorable circumstances

- Pure R&D facility (no users)
- Unique laser system (pulse shaper)
- Well developed diagnostics (high resolution electron spectrometer, etc.); soon: transverse deflecting cavity + dispersive section for longitudinal phase space measurements

## > Possible contribution from PITZ:

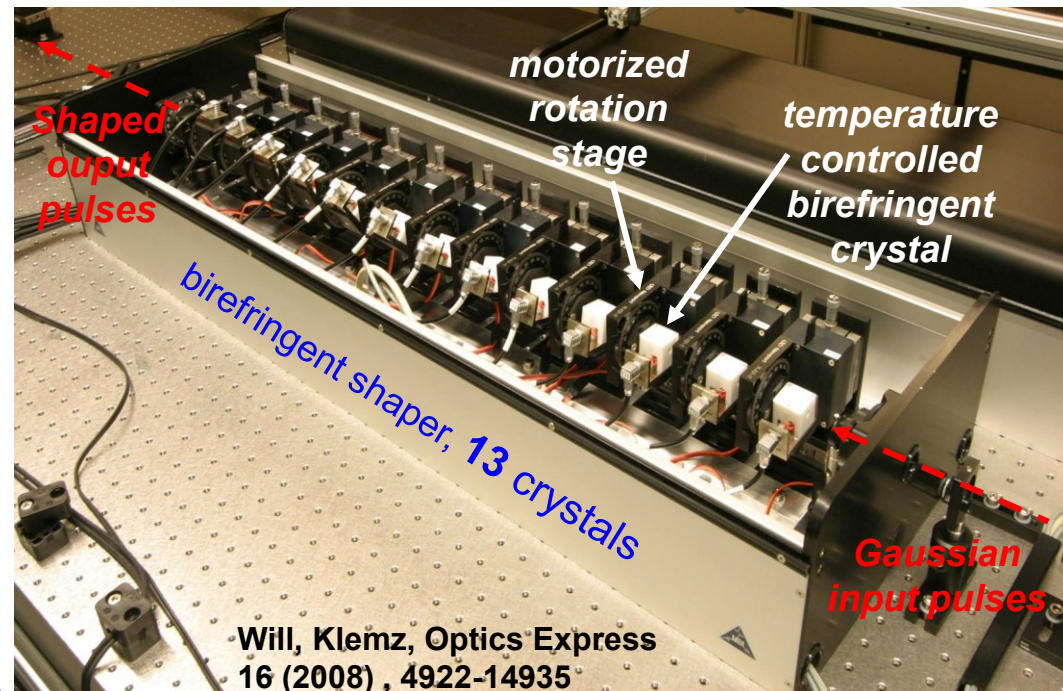
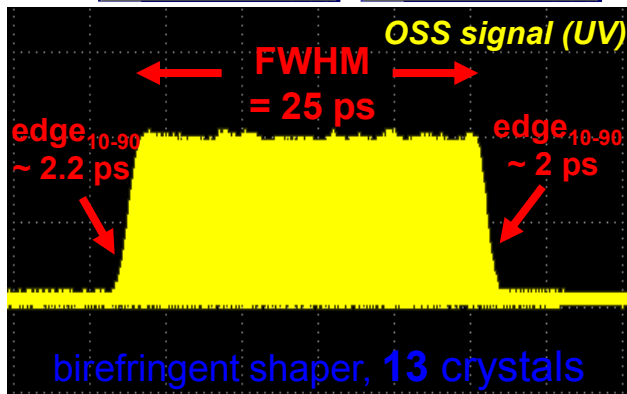
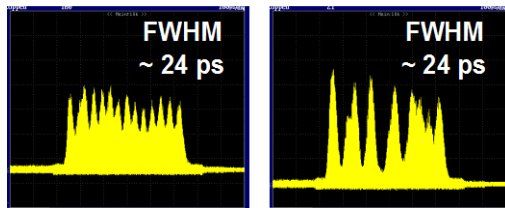
- Self modulation of electron beam
- Later: High transformer ratio (needs bunch compressor)



# Flexible Laser Pulse Formation at PITZ

- Photoinjector laser
- Developed and built by Max-Born Institute Berlin
- Key element: the pulse shaper
  - Contains 13 birefringent crystals. Pulses are split according to polarization. Delay is given by crystal thickness; relative amplitude can be varied freely by adjusting relative angle between crystals

## Simulated pulse-stacker

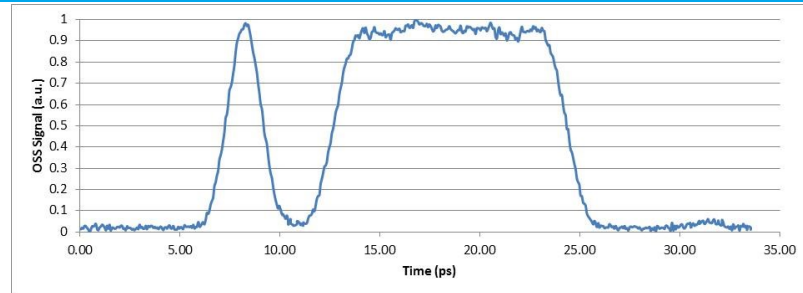


Will, Klemz, Optics Express  
16 (2008), 4922-14935

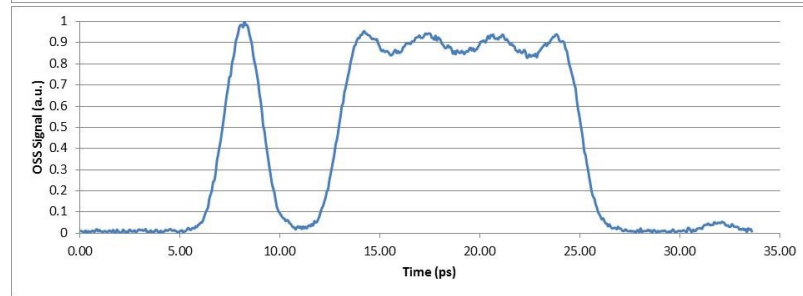


# Experimentally Demonstrated Pulse Shapes

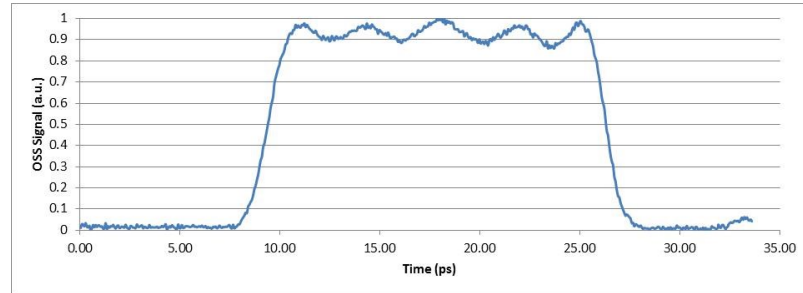
➤ Driver + witness bunch



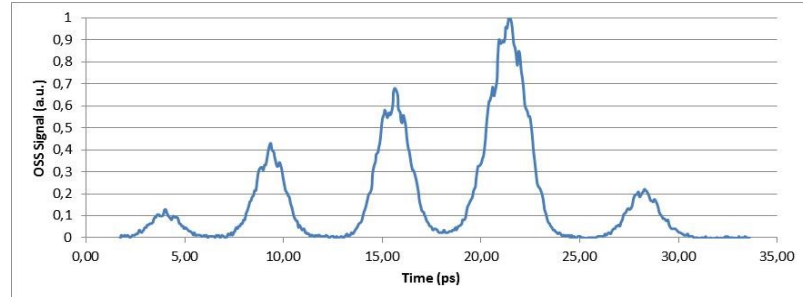
➤ Modulated driver + witness bunch



➤ Modulated driver

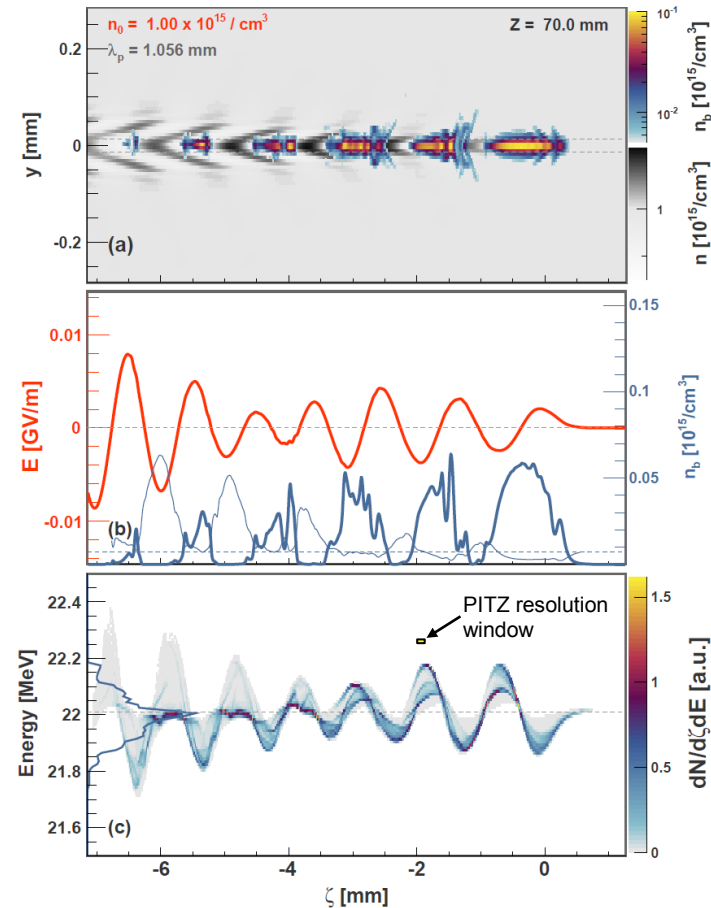


➤ Multi bunches



# 3D PIC (Particle in Cell) Simulation of PITZ Experiment

Beam parameters	Setup 1
Total charge, pC	100
Longitudinal beam position, m	6.44
Horizontal rms beam size, $\mu\text{m}$	42.0
Vertical rms beam size, mm	42.0
Bunch length in FWHM, mm	5.93
Average kinetic energy, MeV	21.5
Peak slice current, A	5.3
Horizontal rms emittance, mm mrad	0.372
Vertical rms emittance, mm mrad	0.372
Peak beam density, $10^{13} \text{ e} / \text{cm}^3$	1.9

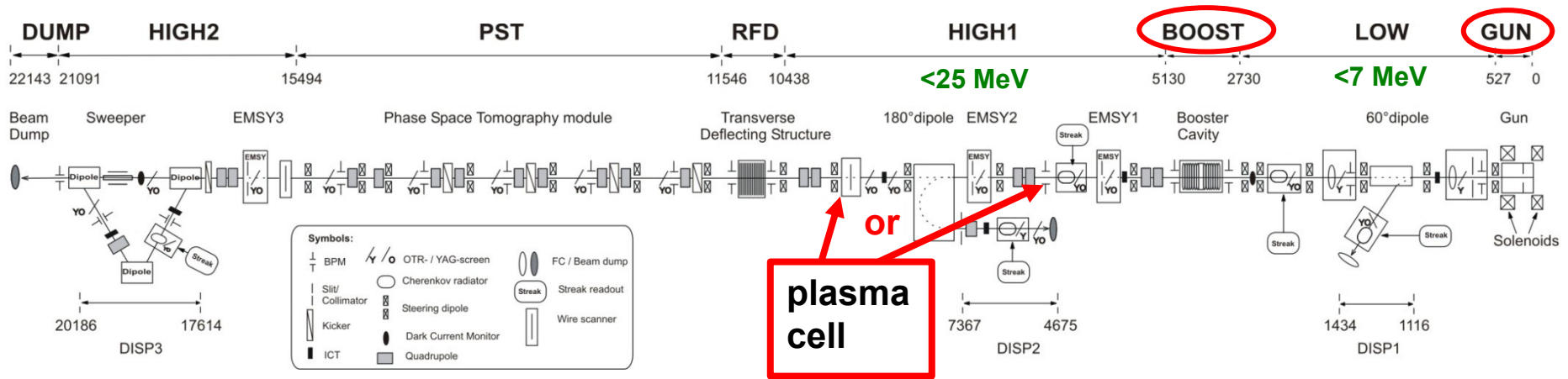


➤ Expected energy modulation  $\approx 400 \text{ keV}$ . PITZ beam energy spread as low as  $\approx 60 \text{ keV}$ . Resolution of TDS/HEDA2:  $10 \text{ keV}$  and  $100 \mu\text{m}$  (Malyutin et al. "Simulation of the Longitudinal Phase Space Measurements With the Transverse Deflecting Structure at PITZ", *Proc. of IPAC 2012, MOPPP034* → **Measurable**)



# Insertion of Plasma Cell into PITZ Setup

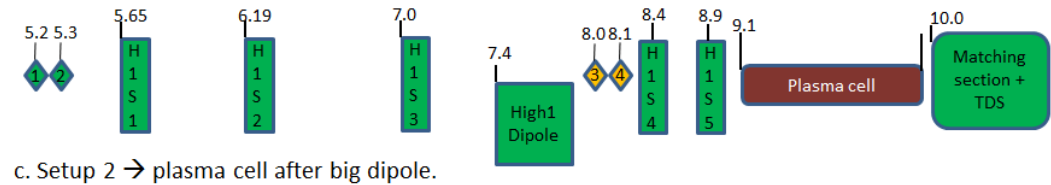
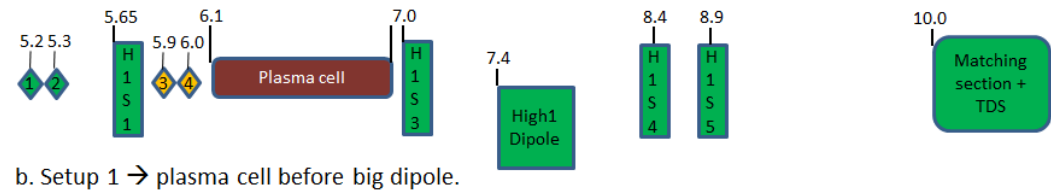
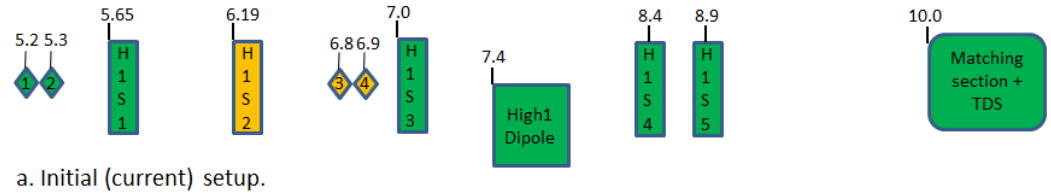
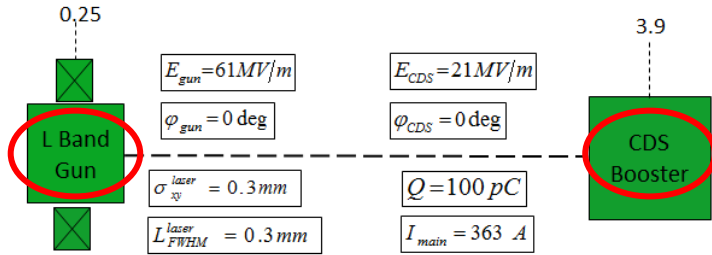
- PITZ 2 setup to be used for first plasma experiments



- Plasma cell has to be between booster and TDS
- Two possible positions, both with a length of about 1m
- Beam dynamics simulations to determine which position is more favorable

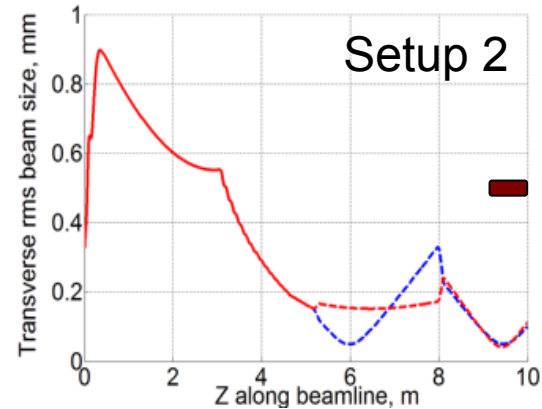
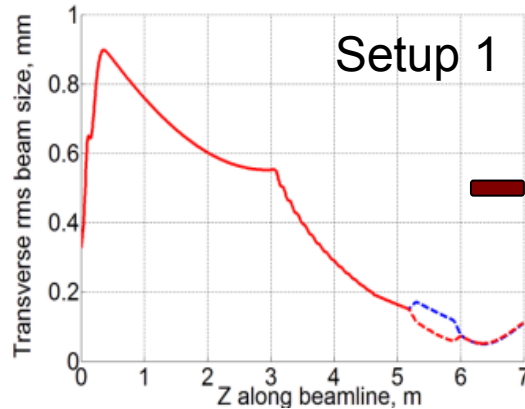
# Simulation: Scenarios for Plasma Cell Insertion

## > Schematic views



## > Electron beam rms size

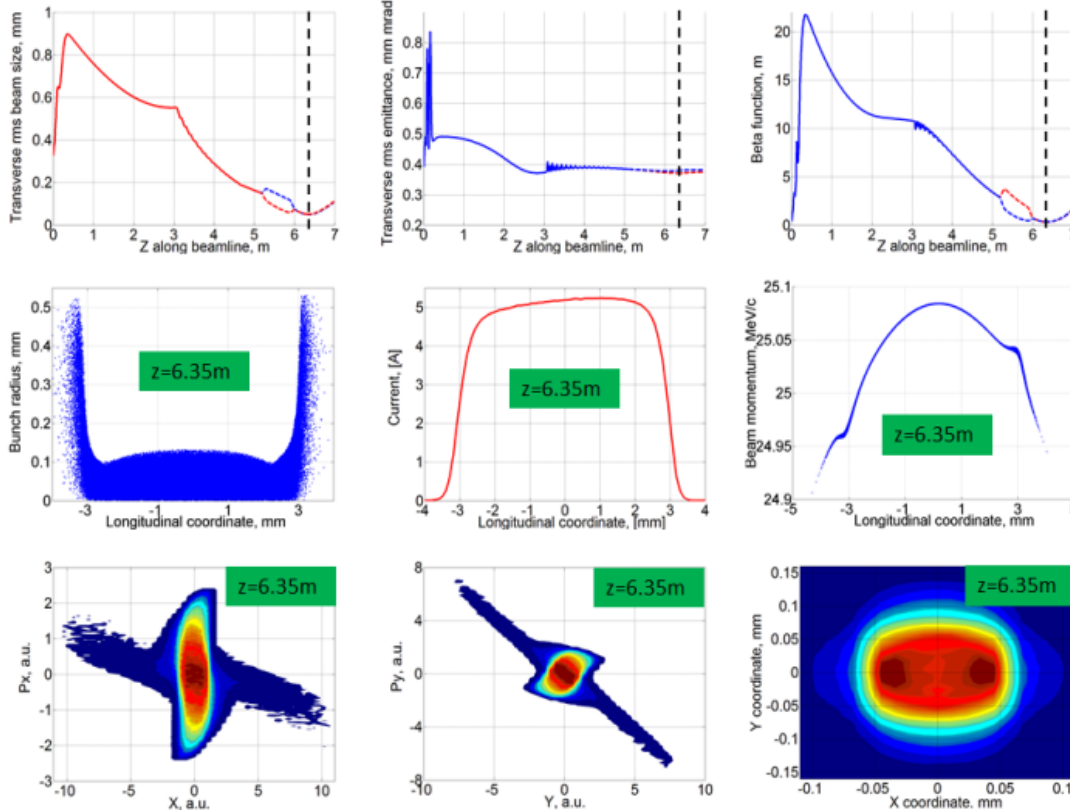
- More complex beam focusing for setup 2





# Simulation: Beam Properties

## ➤ Beam properties for Setup 1 ( $I_{\text{main}} = 363\text{A}$ )



## Comparison of setups

Beam parameters	Before dipole	After dipole
Total charge, pC	100	100
Longitudinal beam position, m	6.35	9.45
Horizontal rms beam size, $\mu\text{m}$	49.8	59.4
Vertical rms beam size, mm	51.2	59.4
Rms bunch length, mm	1.71	1.71
Bunch length in FWHM, mm	5.92	5.92
Average kinetic energy, MeV	24.55	24.55
Rms energy spread, keV	27.5	27.8
Peak slice current, A	5.2	5.2
Horizontal rms emittance, mm mrad	0.37	0.38
Horizontal beam divergence, mrad	0.008	0.09
Vertical rms emittance, mm mrad	0.38	0.36
Vertical beam divergence, mrad	0.002	0.13
Longitudinal rms emittance, keV mm	42.4	42.4
Peak beam density, $10^{12} \text{ e}^- / \text{cm}^3$	9.1	6.6

➤ Setup 1: beam properties acceptable. Smaller beam size, less divergence, higher peak density – overall preferable

## > Three approaches:

1. Plasma discharge
2. RF wave (helicon wave)
3. **Laser ionization**
  - Single photon ionization
    - Linear process
    - Need UV light ( $< 230\text{nm}$ ), e.g. ArF laser
    - Normally partial ionization  $\rightarrow$  percentage is function of local laser intensity (saturation curve)
  - Field ionization
    - Nonlinear process
    - Laser wavelength not important, e.g. Ti:Sapphire or  $\text{CO}_2$  laser
    - Threshold process  $\rightarrow$  Complete ionization in well defined volume



# Lithium Plasma Cell

## > Principle:

- Evaporate Lithium in central pipe (700°C)
- Define beginning and end of Lithium zone with steep temperature gradient and Helium buffer gas
- Once pressure regions have stabilized:
  - Ionize Lithium gas with laser
  - Inject particle beam for PWA experiment

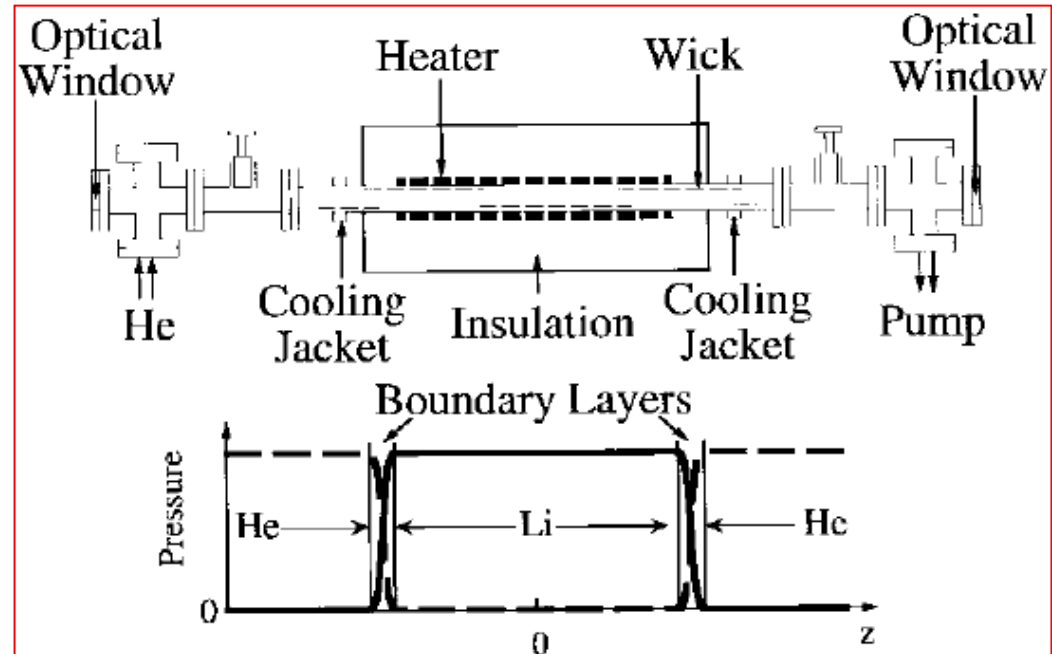
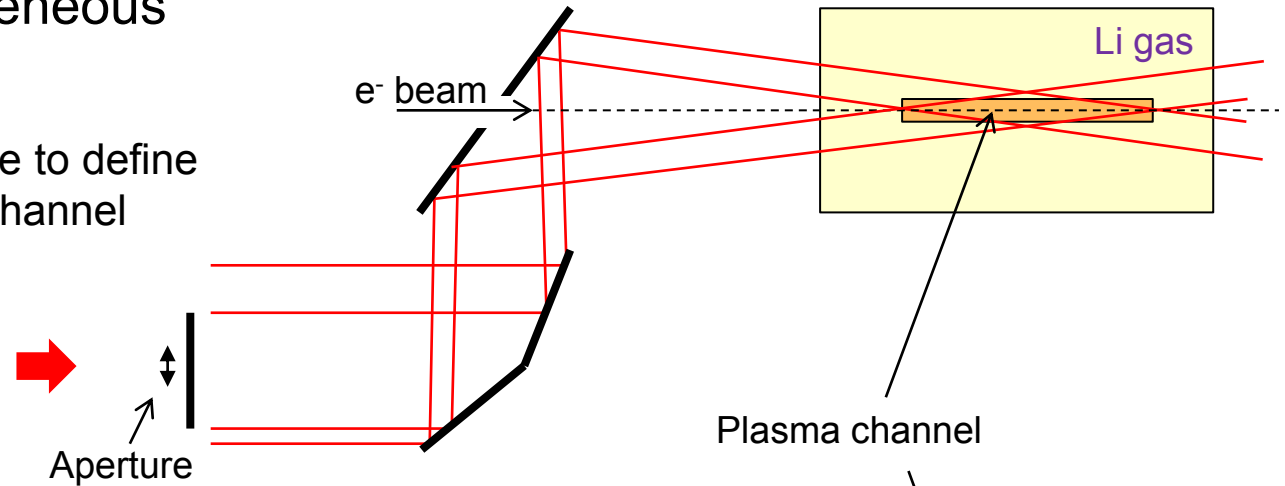


Figure from: P. Muggli et al. "Photo-Ionized Lithium Source for Plasma Accelerator Applications", *IEEE Trans. Plasma Science* **27** (1999), pp. 791-799

# Optics for Laser Plasma Generation – Axial Coupling

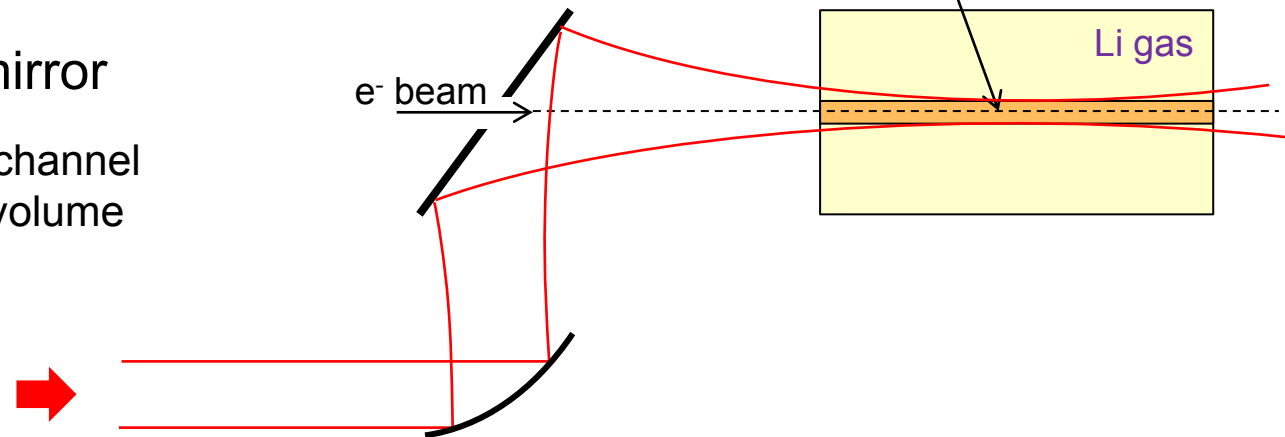
## > Axicon for homogeneous ionization profile

- Adjustable aperture to define length of plasma channel



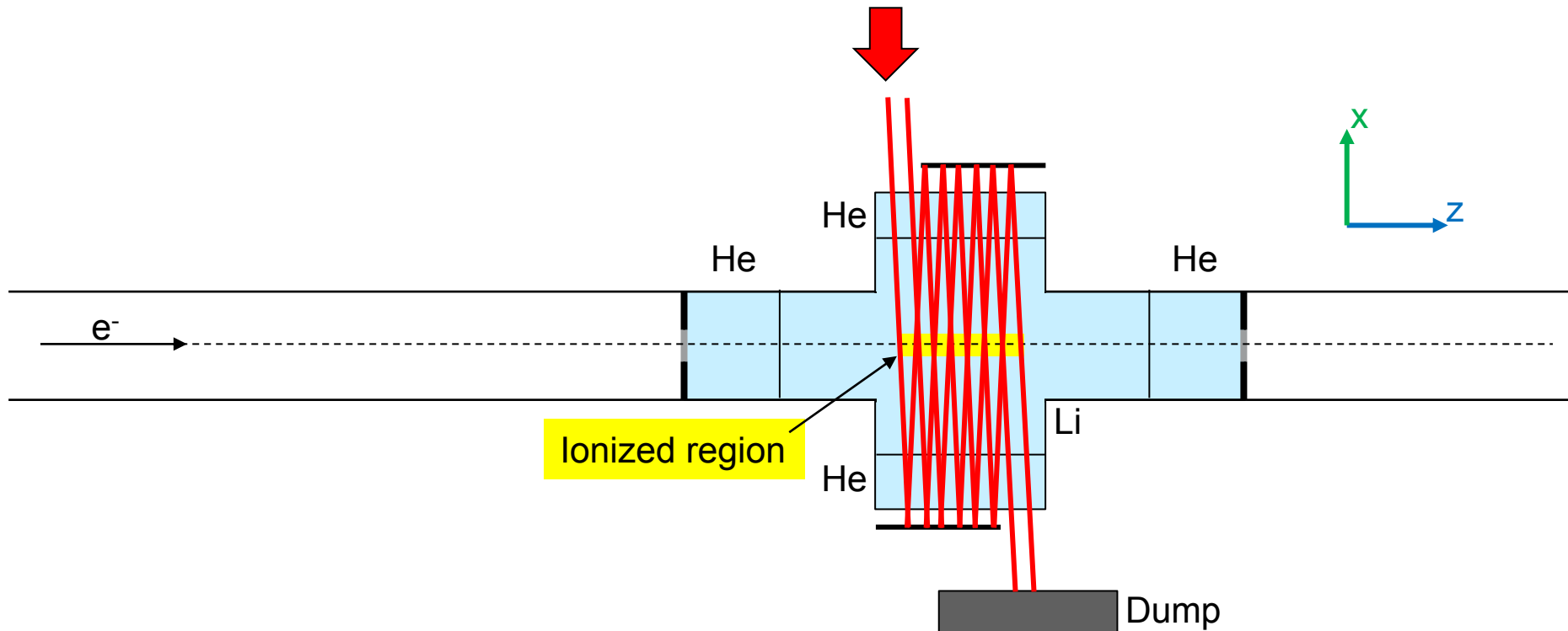
## > Simple focusing mirror

- Length of plasma channel defined by Li gas volume



# Plasma Ionization –Side Coupling

- Independent optimization of electron and laser paths possible
- Setup:



# Plasma Cell Assembly: Sketch

Design:  
Gerald Koss

Turbo pump

Preliminary Version

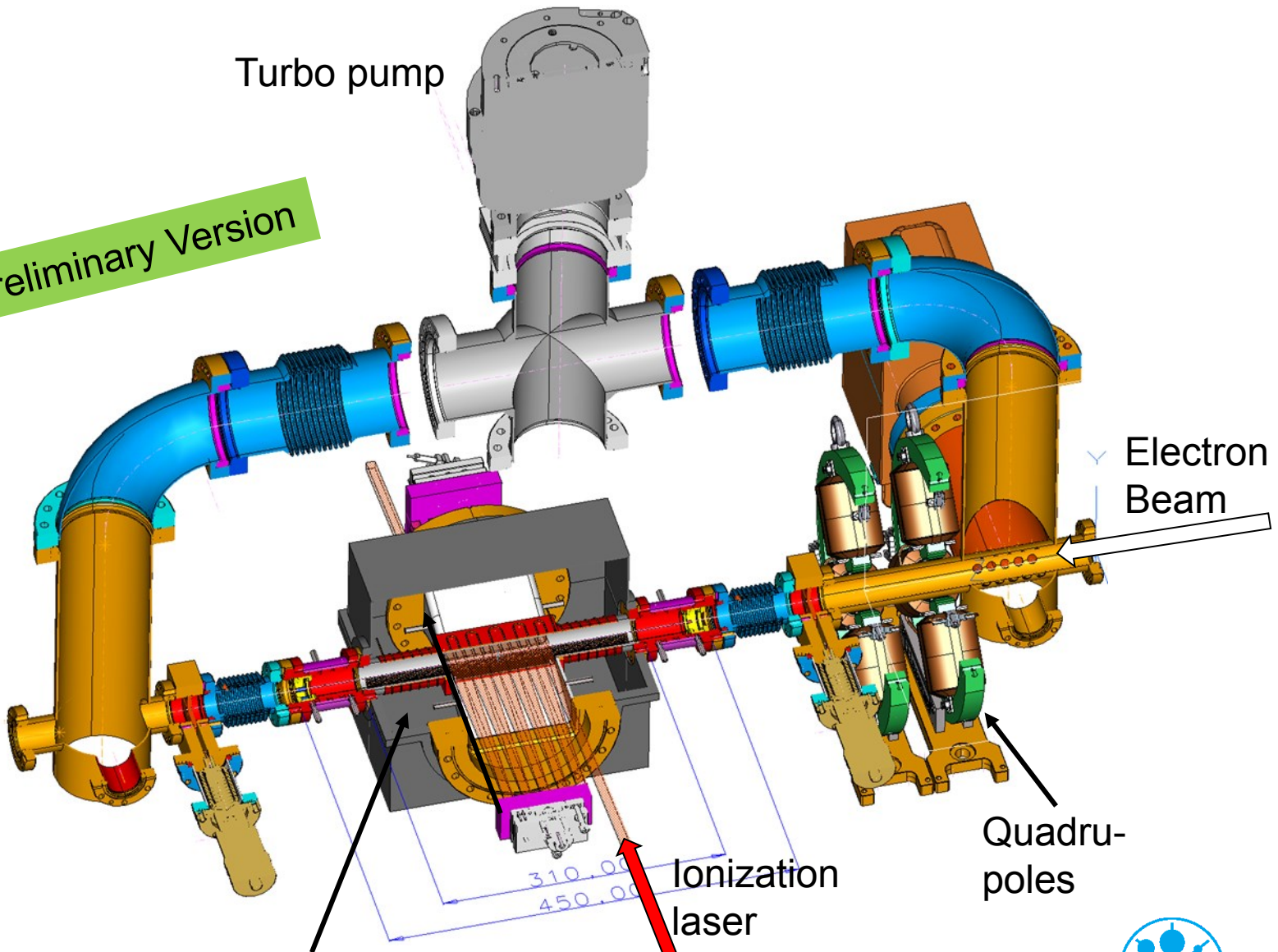
Electron Beam

To  
diagnostics

Quadru-  
poles

Ionization  
laser

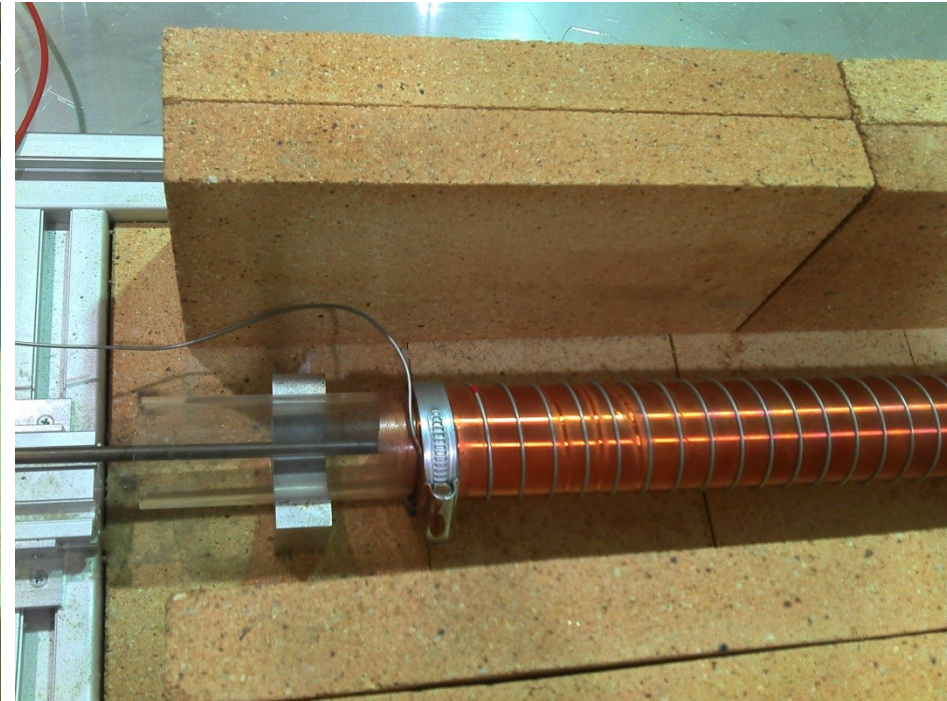
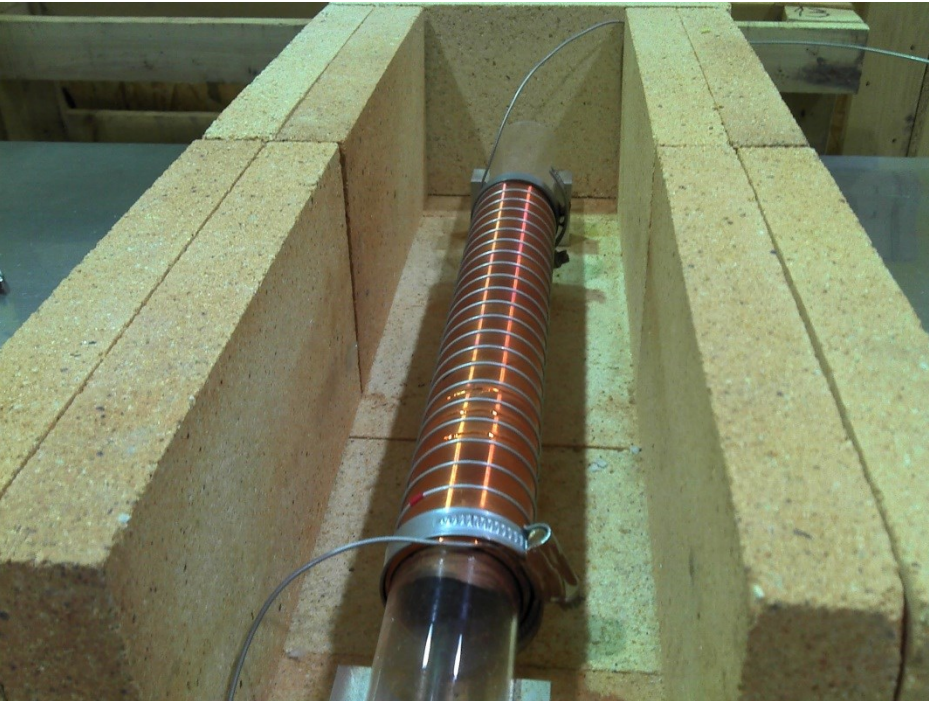
Plasma cell





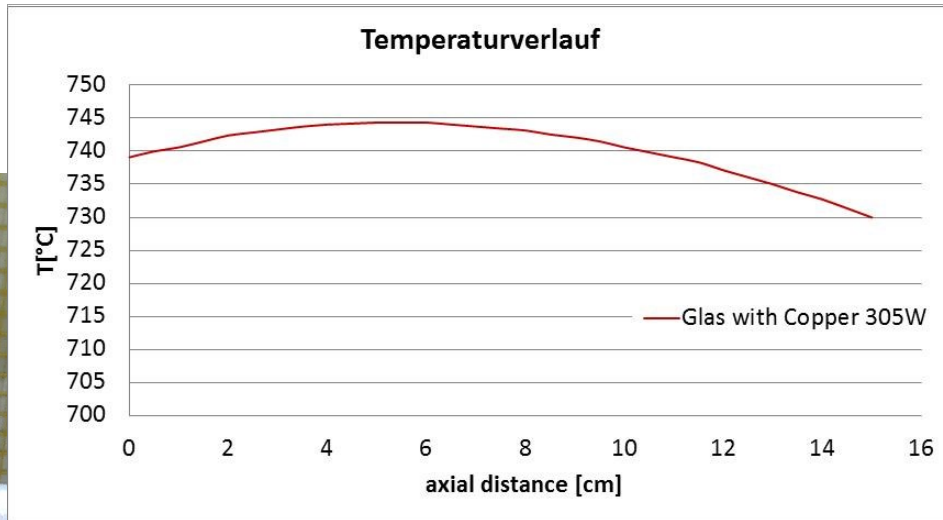
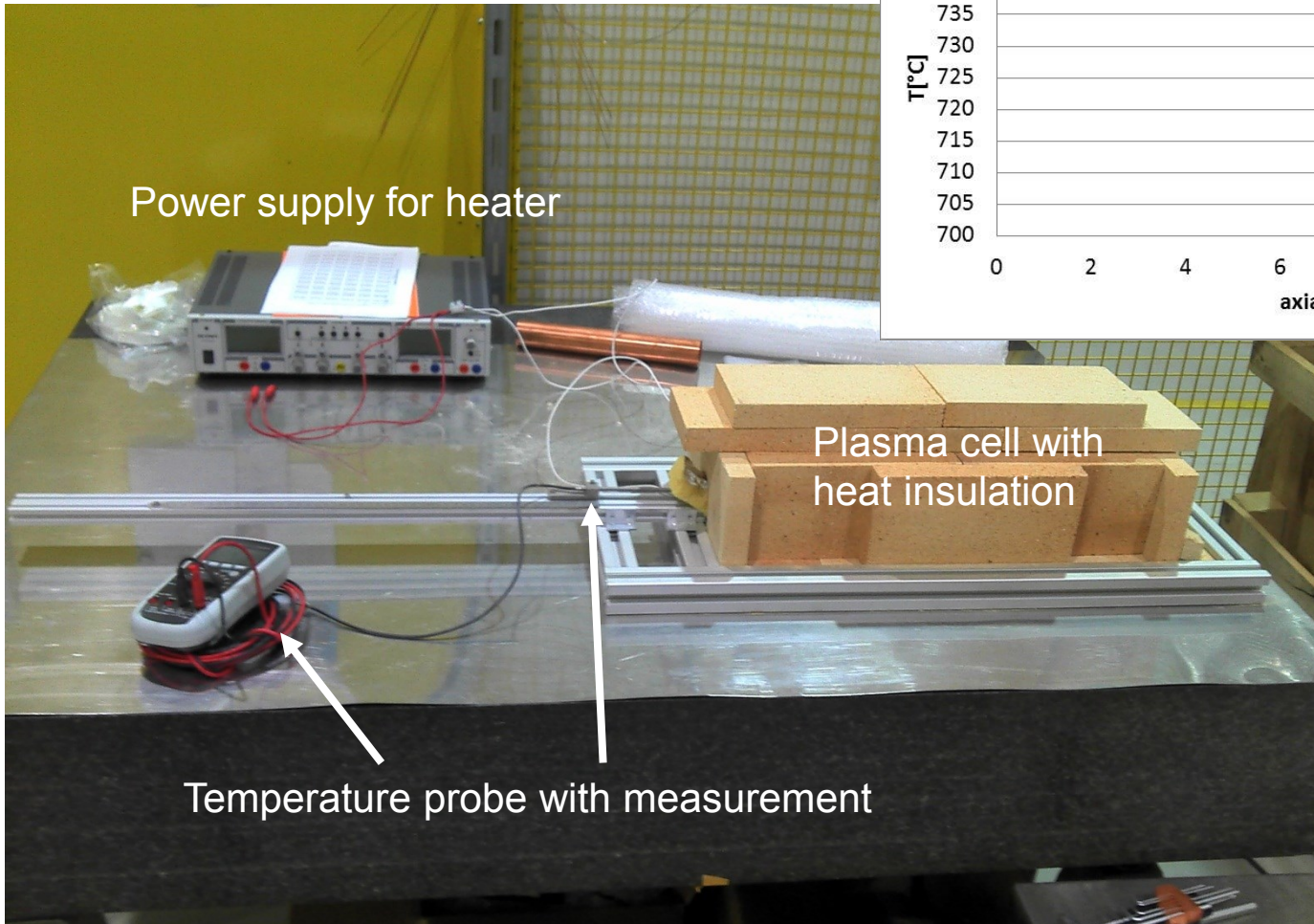
# Heat Pipe Oven Prototype

- Inner glass tube; outer copper tube with spiral groove to hold heating wire (Thermocoax TET; 1.5mm diameter;  $5.5\Omega/m$ )
- Length of heating region: 30cm



# Experiments have started with Plasma Cell Prototype

- First: Measurement of temperature profile with air in plasma cell tube



- Copper tube helps to homogenize temperature distribution:  $\pm 2^{\circ}\text{C}$  ( $< 1\%$ ) over 10cm
- Temperature is high enough: need  $\approx 650^{\circ}\text{C}$  in PITZ experiment



# Multi Bunches: High Transformer Ratio

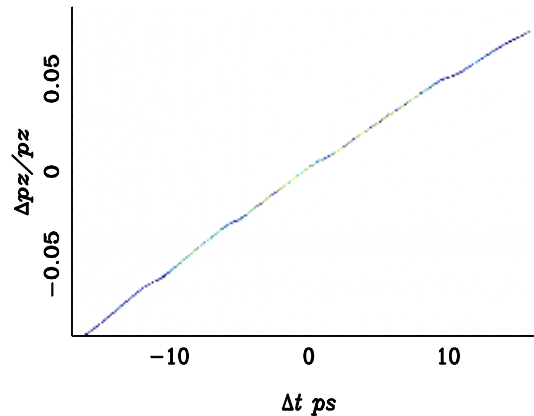
➤ Plasma Acceleration: e.g. 5 bunchlets within bunch → **transformer ratio >2**

**Setup:** - use PITZ2 beamline with gun, booster, and matching quads up to  $z=7\text{m}$   
 - install a short bunch compressor (dogleg)

**ASTRA simulations** through gun and booster up to  $z=5\text{m}$

**Parameters:**

Q = 170 pC in 5 pulses  
 100 000 particles  
 Gun phase: 10 deg  
 Booster phase: 40 deg



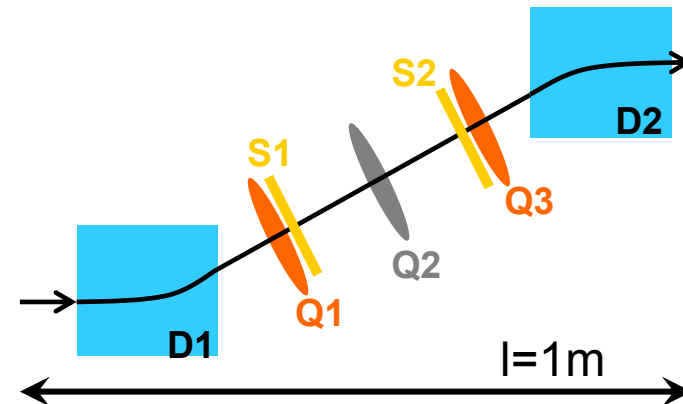
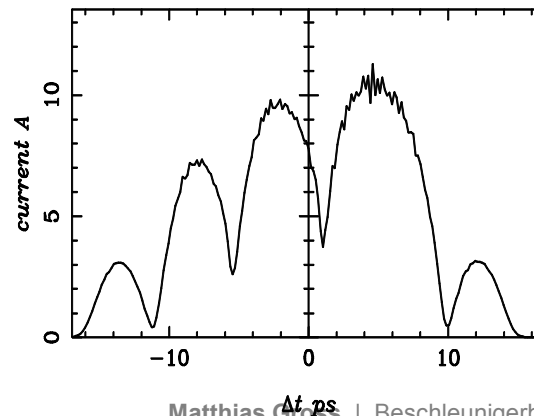
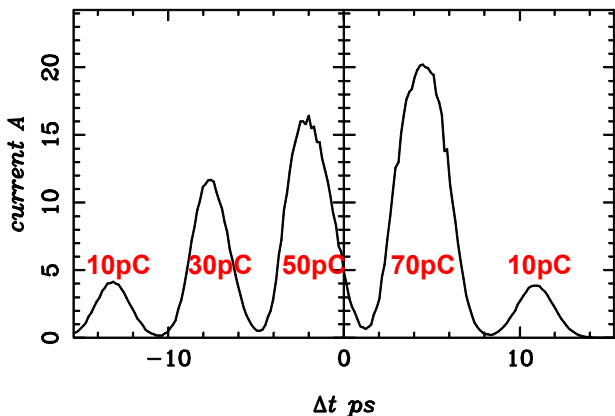
Longitudinal phase space at  $z=5\text{m}$

use **Elegant** for matching and the dogleg design (ongoing)

**BC layout:**

compression factor  $C = 4$   
 $R_{56} = 0.15$   
 Total length  $l = 1\text{m}$   
 dipoles:  $r = 0.6\text{m}$ ,  $\alpha = 60\text{ deg}$

Longitudinal laser profile at the cathode



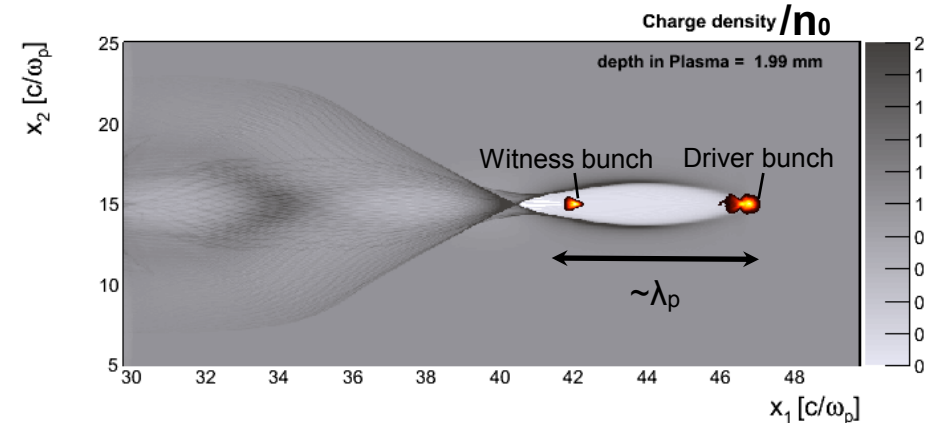
**Design with 2 doglegs (↑↓) on the way**



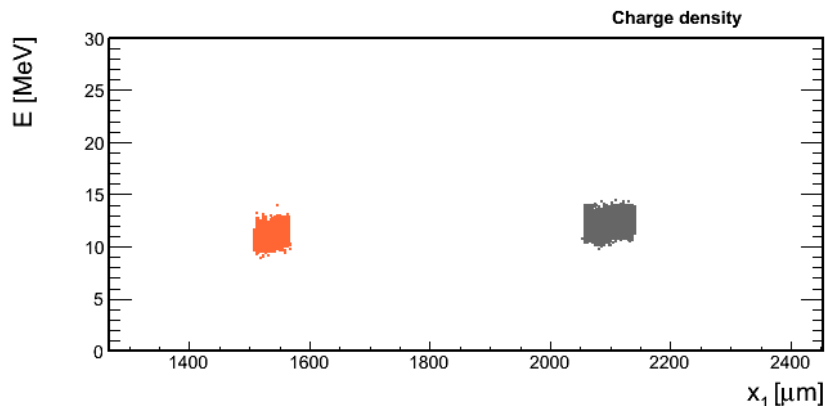
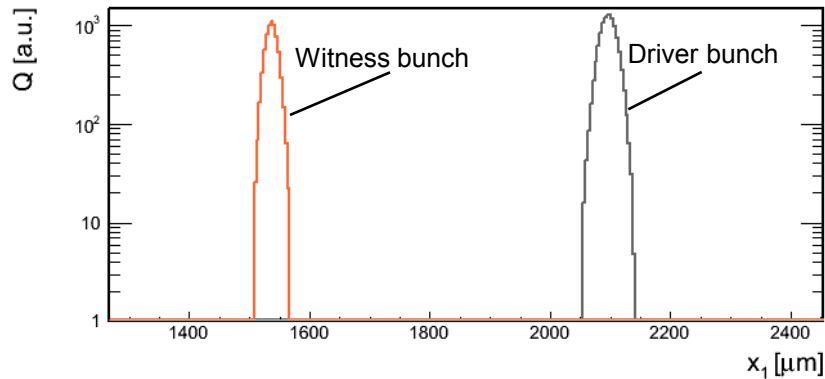
# Very Preliminary Results: Needs Optimization

The witness bunch falls in the region where the wakefield is maximum.

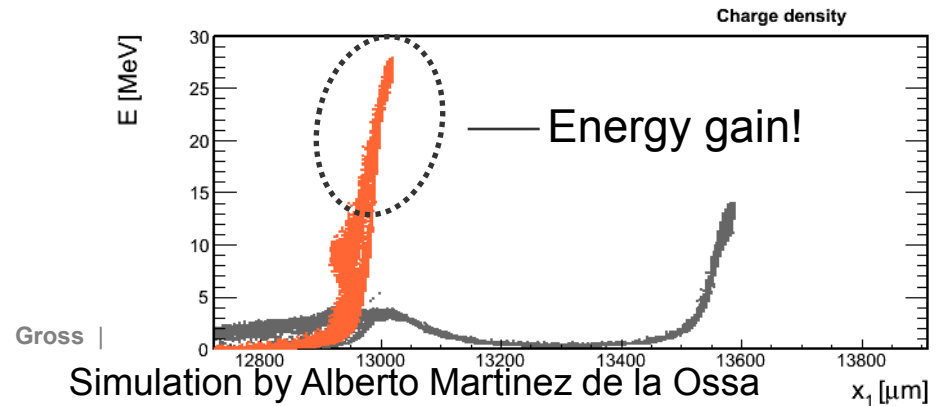
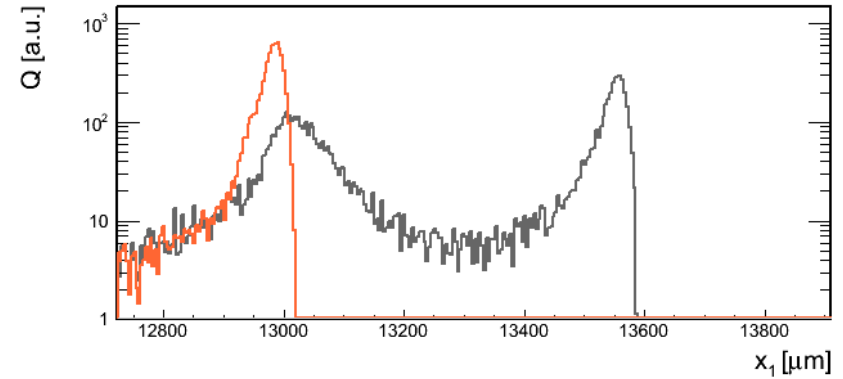
**In approx. 1 cm of propagation in the plasma, a fraction of the electrons in the witness bunch double their energy.**



Bunches at the beginning:



Bunches after 1 cm in plasma:



Simulation by Alberto Martinez de la Ossa

# Outlook

- 2013: First experiments with plasma cell in laboratory
- 2014: Characterization of energy modulation of electron beam in plasma
- Then: Insertion of bunch compressor – experiments with high transformer ratio etc.
- Cooperation with SLAC, CERN etc.



# Summary

- > PWA Experiments are planned at PITZ
  - Now: Characterization of electron beam self modulation
  - Later: High transformer ratio
- > Utilization of good diagnostics and unique laser system
- > Simulations show promising results
  - Electron sub bunching and energy modulation with current setup
  - Energy gain with bunch compressor
- > First experiments with plasma cell prototype

