Studies for Particle Driven Plasma Acceleration at PITZ

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

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Grömitz,
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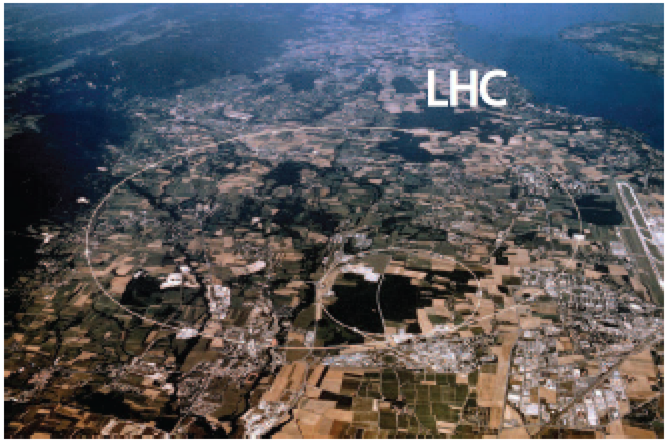
HELMHOLTZ | ASSOCIATION

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)

$\Rightarrow$ high gradient requires high density: $E_z \propto n^{1/2}$
$\Rightarrow$ large wake requires resonance beam: $L_b \sim \lambda_p \propto n^{-1/2}$

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

$\Rightarrow$ high accelerating gradient requires **short** bunches $\sigma_z \lesssim 100\ \mu\mathrm{m}$
$\Rightarrow$ existing proton machines produce **long** bunches $\sigma_z \sim 10$ cm

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

Does this work ?
→Dephasing ?
→Hose instability ?

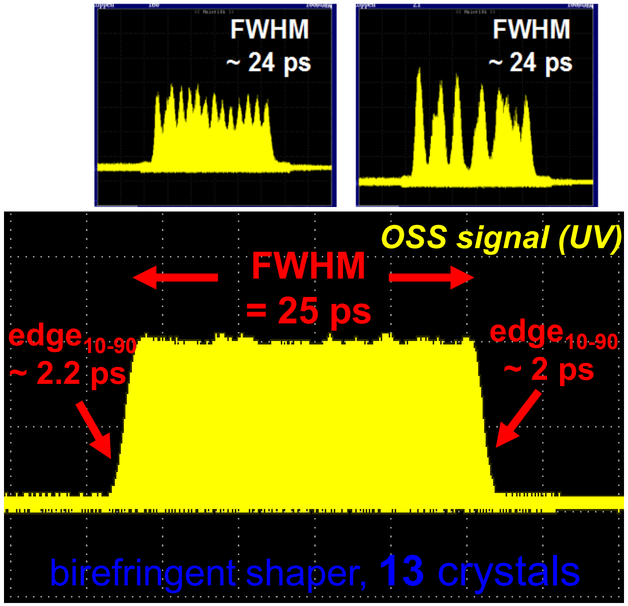
Why Experiments at PITZ?

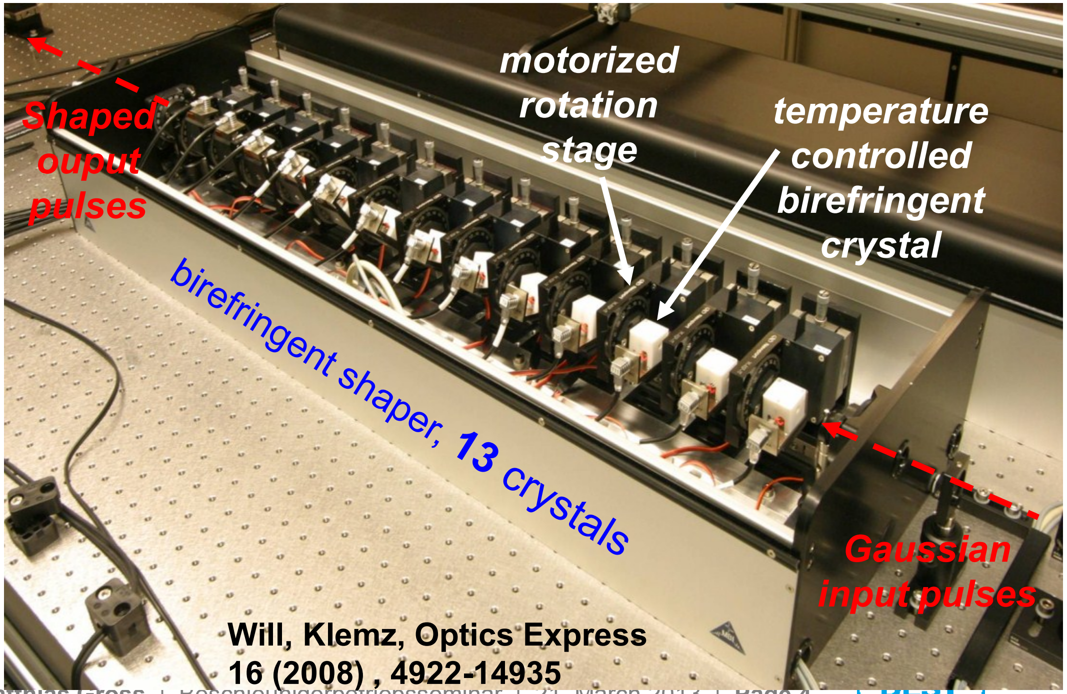
- Favorable circumstances
  - Pure R&D facility (no users)
  - Unique laser system (pulse shaper)
  - Well developed diagnostics (high resolution electron spectrometer, etc.); soon: transverse deflecting cavity + dispersive section for longitudinal phase space measurements
- Possible contribution from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

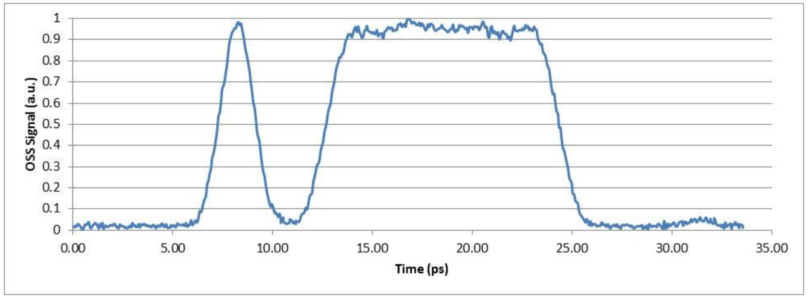
Simulated pulse-stacker



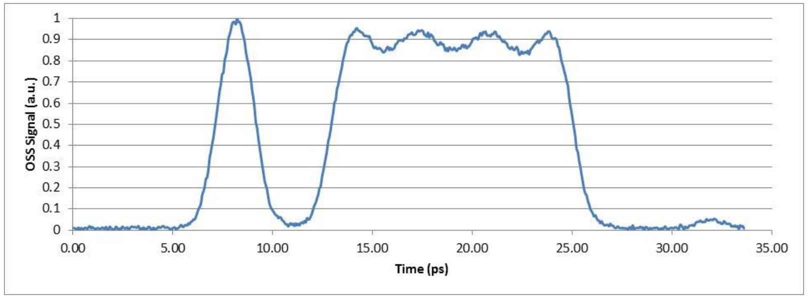


Experimentally Demonstrated Pulse Shapes

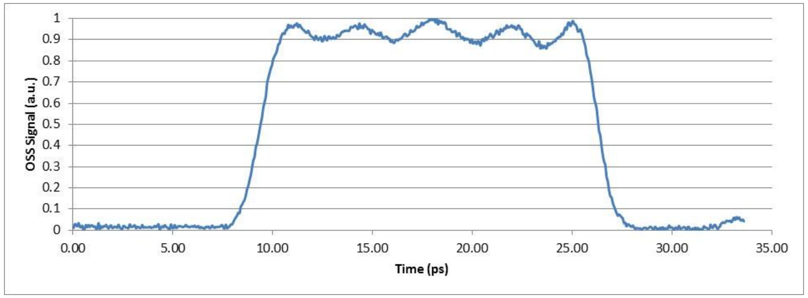
- Driver + witness bunch



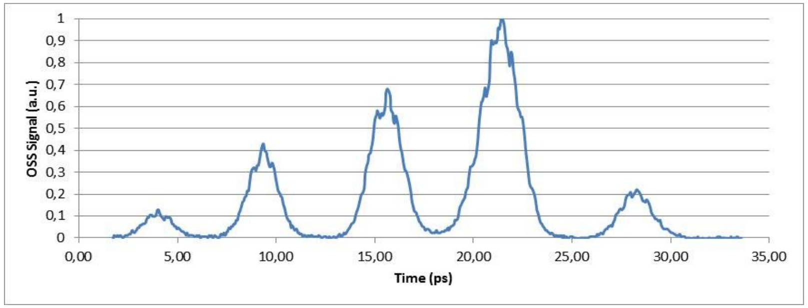
- Modulated driver + witness bunch



- Modulated driver

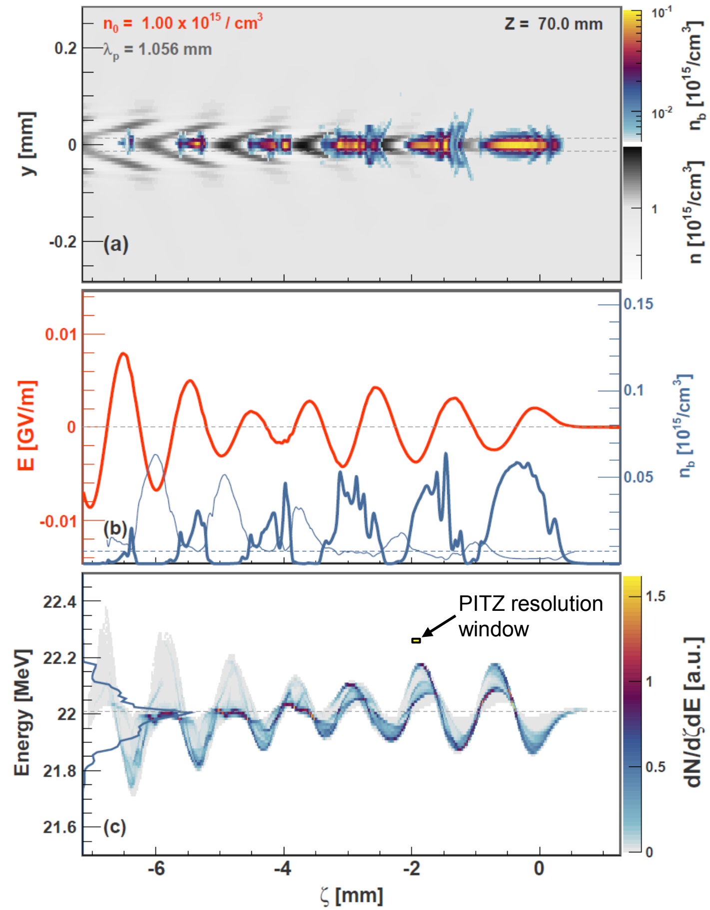


- Multi bunches



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, um	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 e / cm^3	1.9

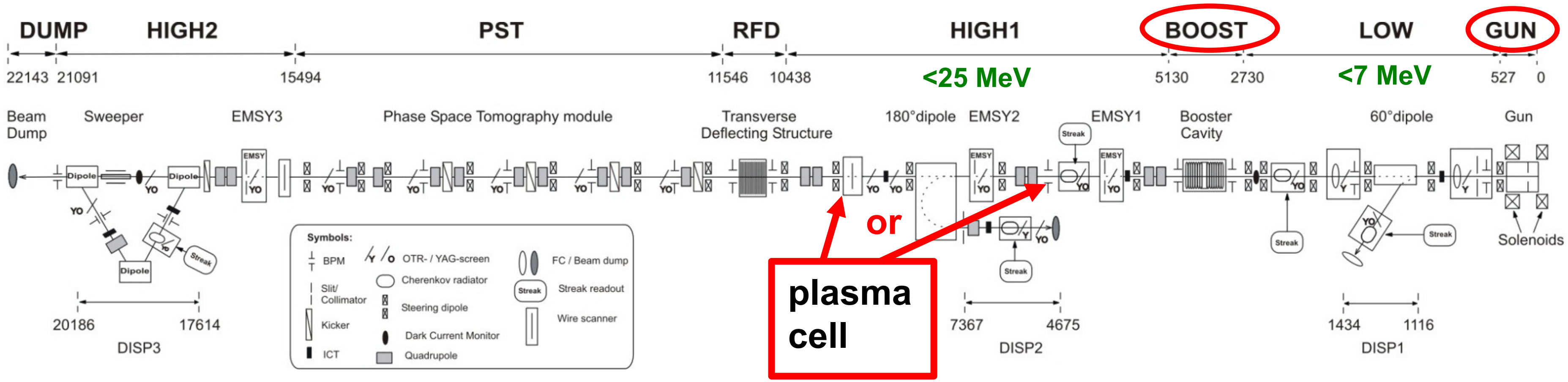


> Expected energy modulation ≈400 keV. PITZ beam energy spread as low as ≈60keV. Resolution of TDS/HEDA2: 10keV and 100µm (Malyutin et al. "Simulation of the Longitudinal Phase Space Measurements With the Transverse Deflecting Structure at PITZ", *Proc. of IPAC 2012, MOPPP034* → Measurable

Simulations:
Alberto Martinez de la Ossa

Insertion of Plasma Cell into PITZ Setup

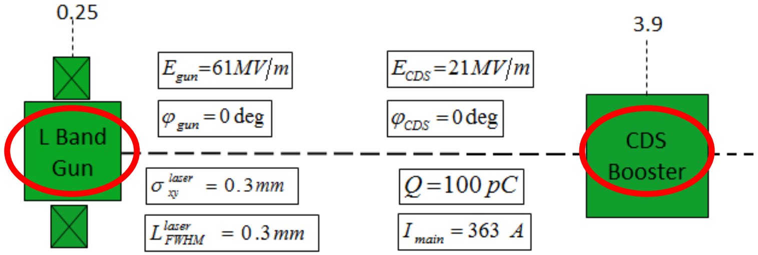
- PITZ 2 setup to be used for first plasma experiments

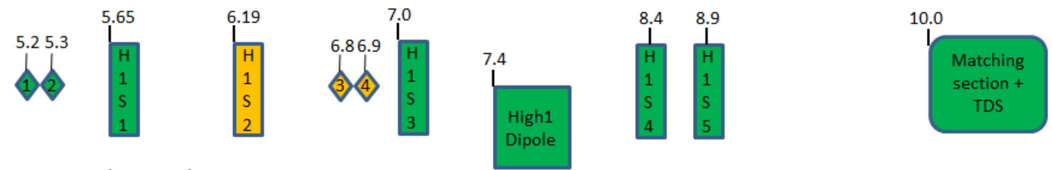


- Plasma cell has to be between booster and TDS
- Two possible positions, both with a length of about 1m
- Beam dynamics simulations to determine which position is more favorable

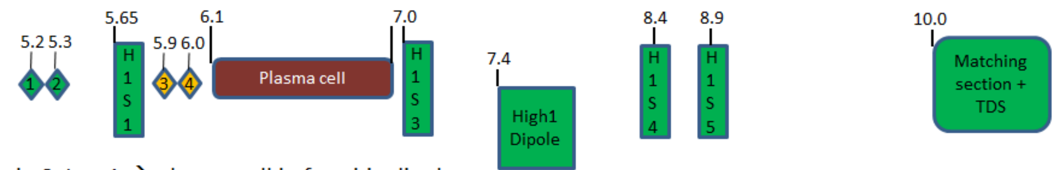
Simulation: Scenarios for Plasma Cell Insertion

- Schematic views

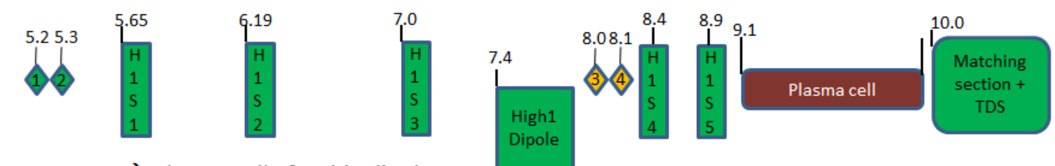




a. Initial (current) setup.

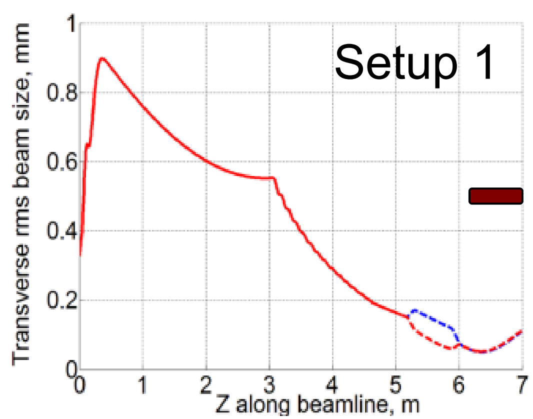


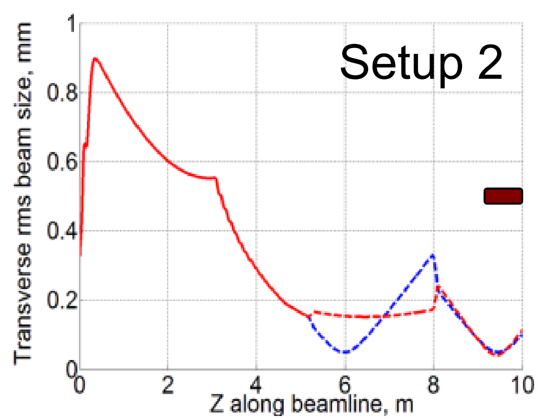
b. Setup 1 → plasma cell before big dipole.



c. Setup 2 → plasma cell after big dipole.

- Electron beam rms size
  - More complex beam focusing for setup 2

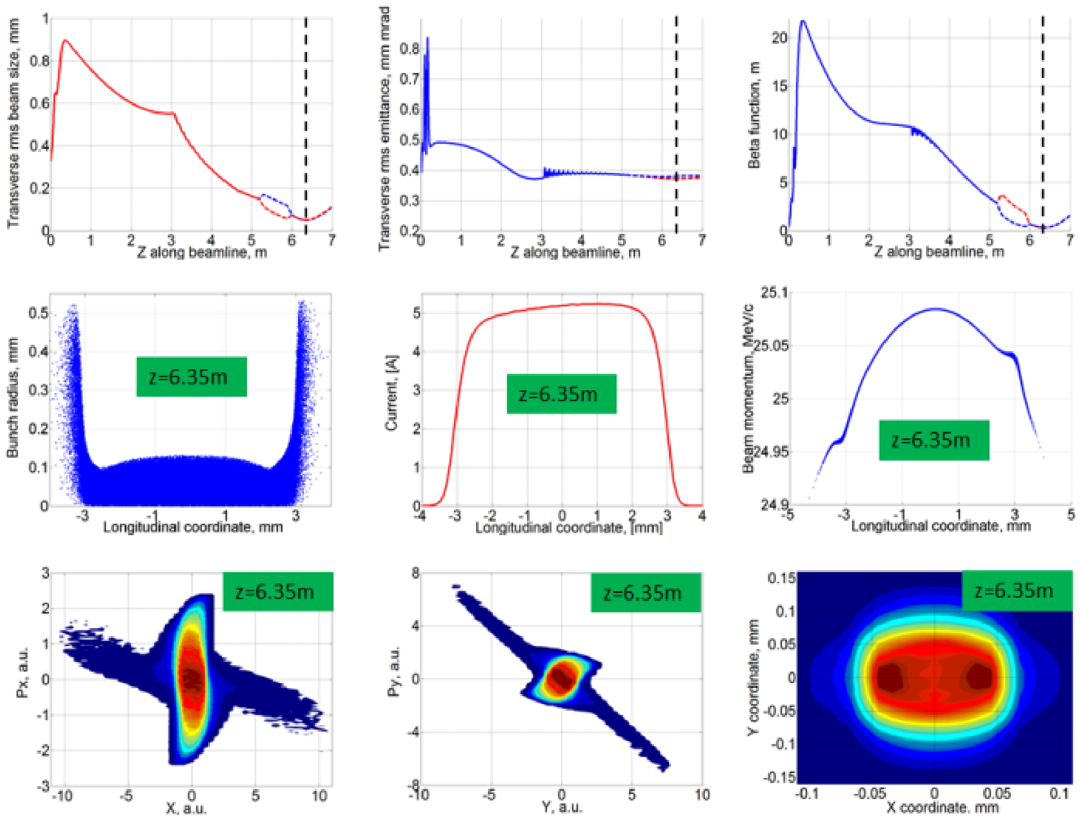




Simulations:
Martin Khojoyan

Simulation: Beam Properties

> Beam properties for Setup 1 (I_{main} = 363A)



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, um	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 e / cm^3	9.1	6.6

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

Simulations:
Martin Khojoyan

Key Topic: Ionization of Plasma Channel

> Three approaches:

1. Plasma discharge
2. RF wave (helicon wave)
3. **Laser ionization**
   - Single photon ionization
     - Linear process
     - Need UV light (< 230nm), e.g. ArF laser
     - Normally partial ionization → percentage is function of local laser intensity (saturation curve)
   - Field ionization
     - Nonlinear process
     - Laser wavelength not important, e.g. Ti:Sapphire or CO_2 laser
     - Threshold process → 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

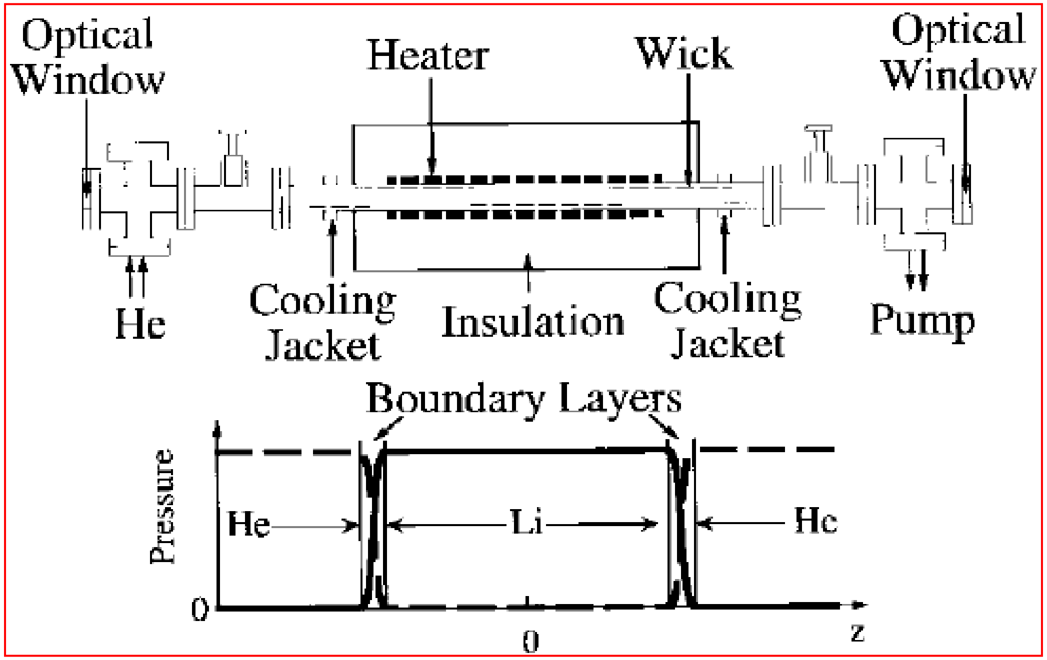
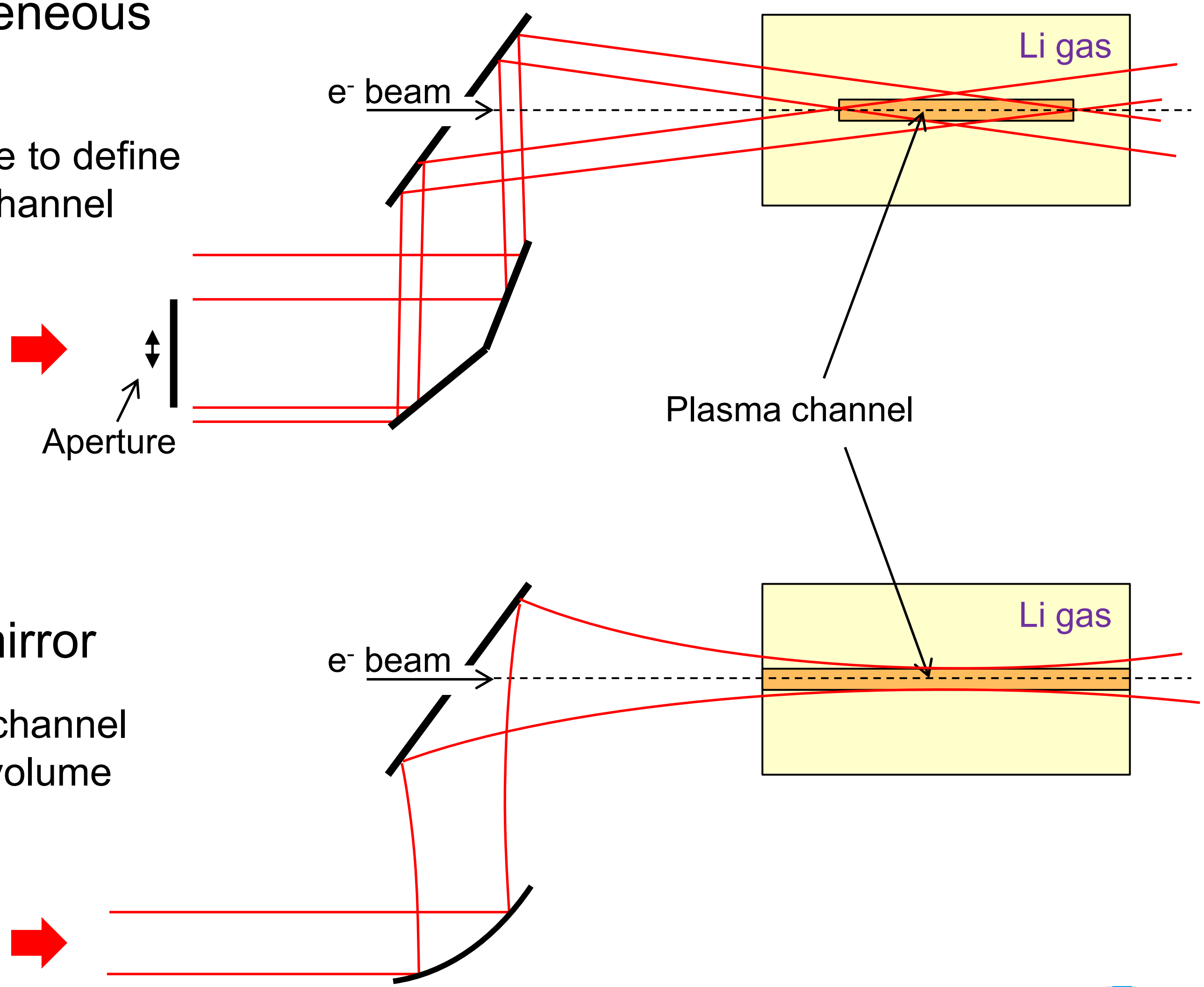


Figure from: P. Muggli et al. “Photo-Ionized Lithium Source for Plasma Accelerator Applications”, *IEEE Trans. Plasma Science* **27** (1999), pp. 791-799

Optics for Laser Plasma Generation – Axial Coupling

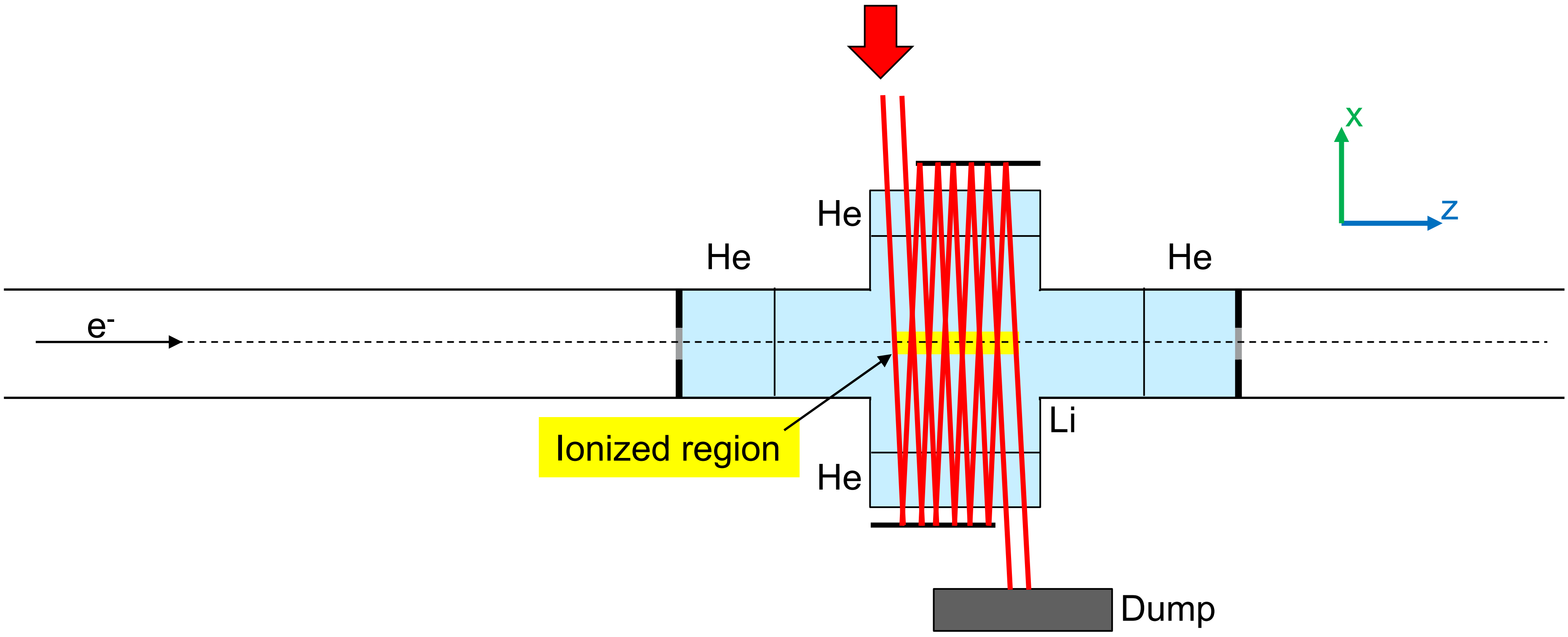
- Axicon for homogeneous ionization profile
  - Adjustable aperture to define length of plasma channel
- Simple focusing mirror
  - Length of plasma channel defined by Li gas volume



DESY

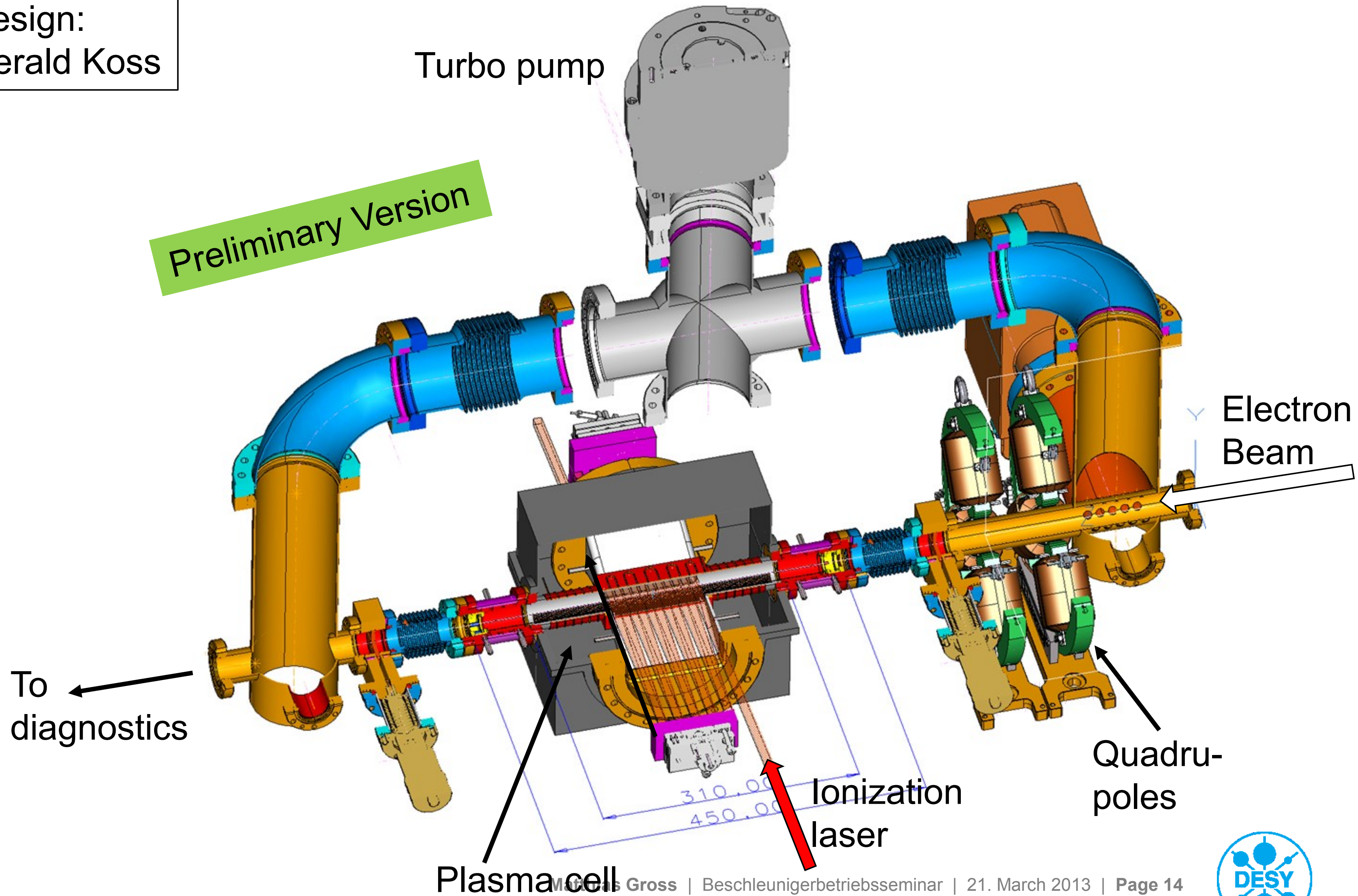
Plasma Ionization –Side Coupling

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



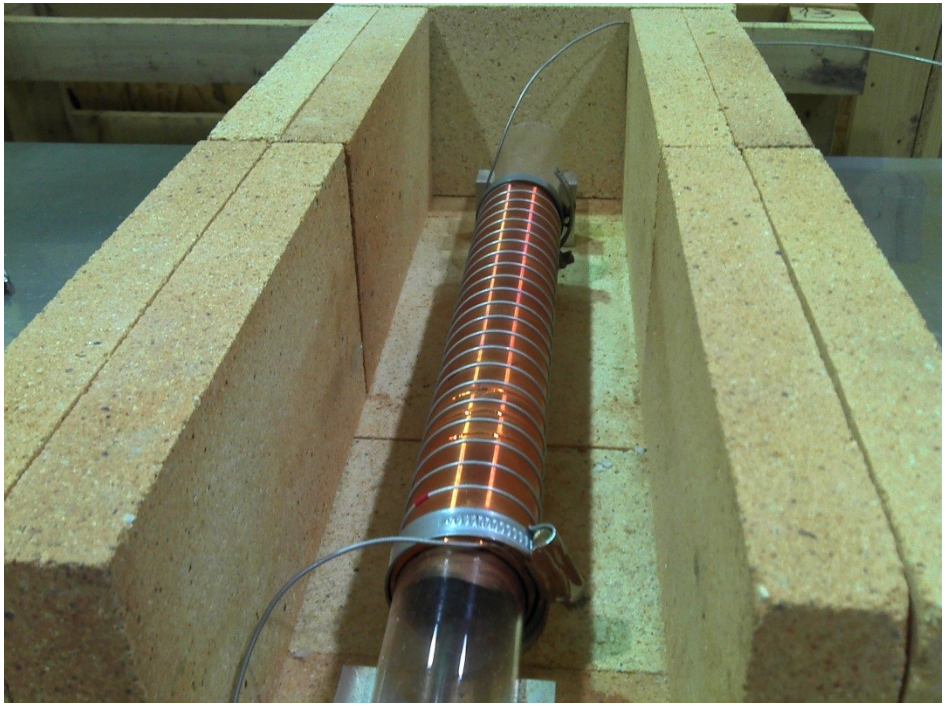
Plasma Cell Assembly: Sketch

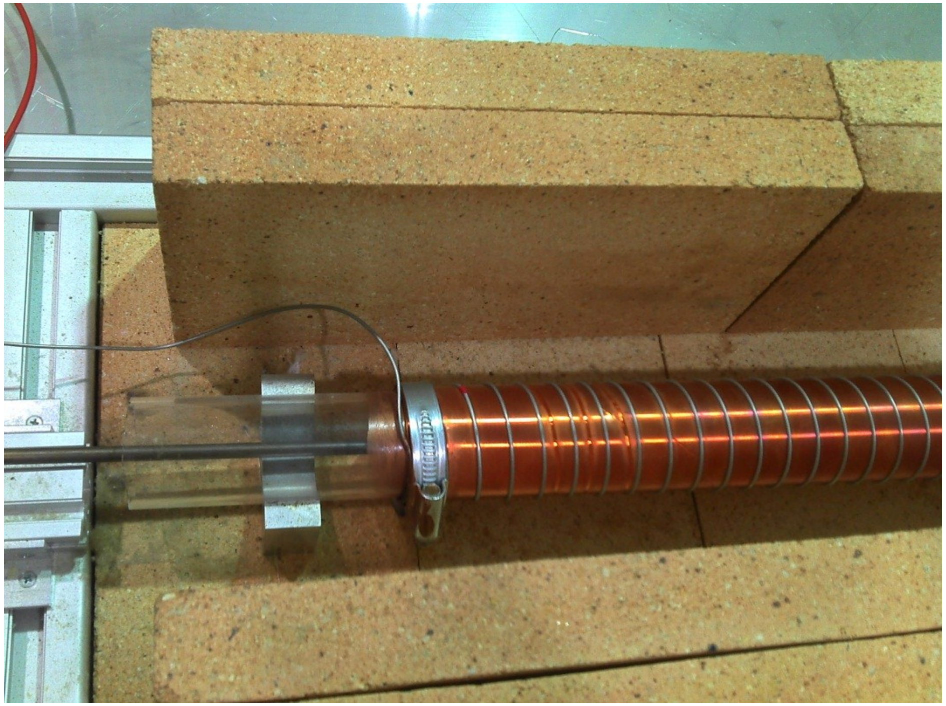
Design:
Gerald Koss



Heat Pipe Oven Prototype

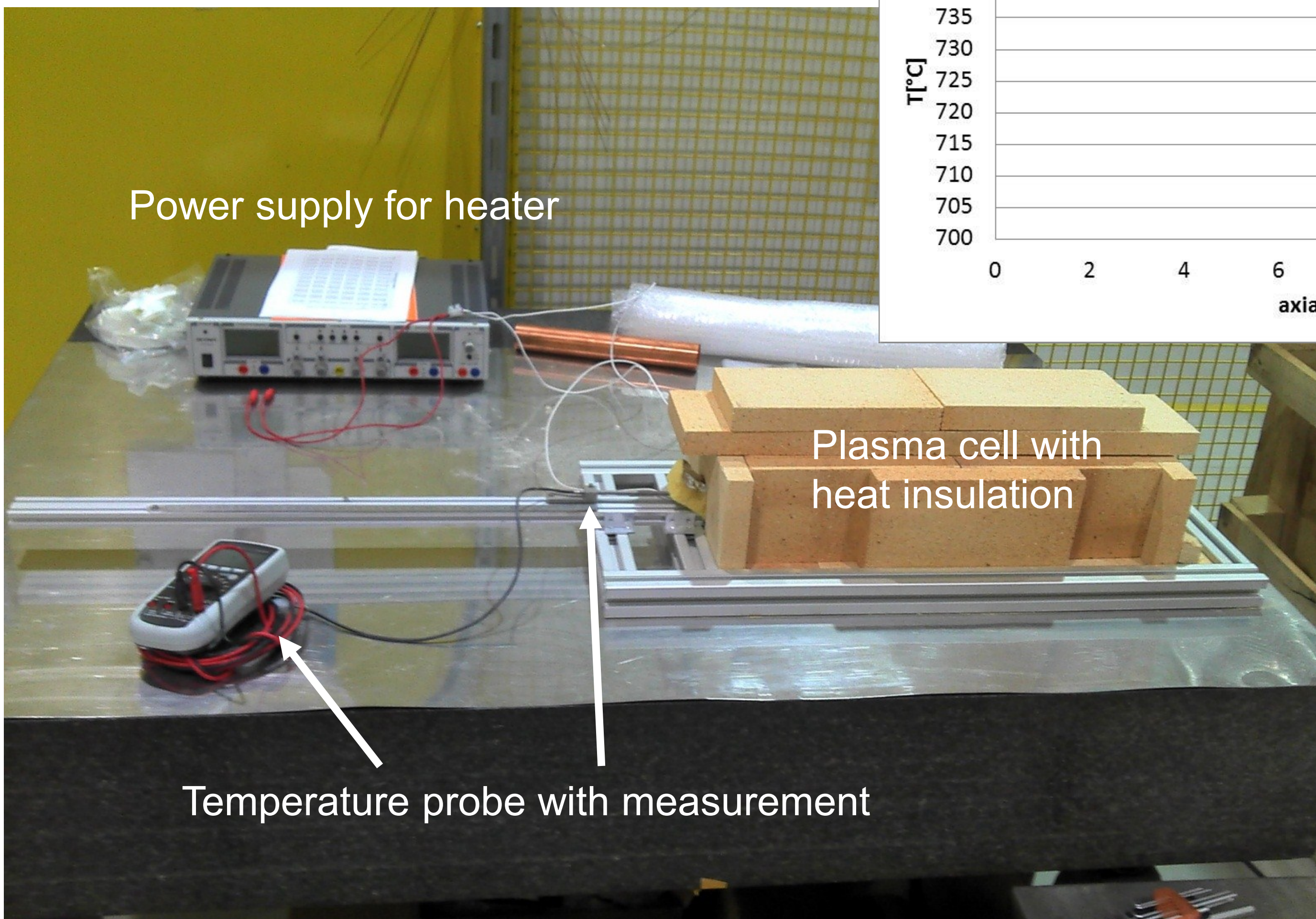
- Inner glass tube; outer copper tube with spiral groove to hold heating wire (Thermocoax TET; 1.5mm diameter; 5.5Ω/m)
- Length of heating region: 30cm

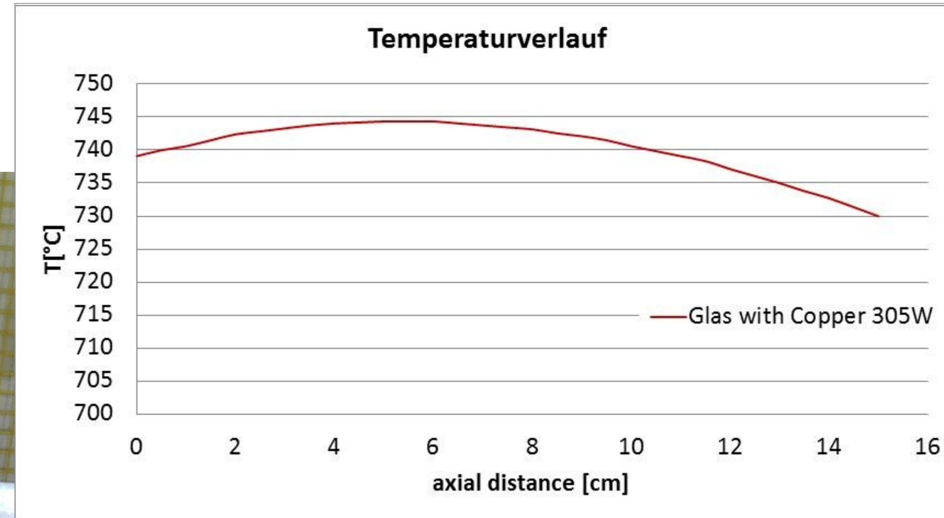




Experiments have started with Plasma Cell Prototype

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





- Copper tube helps to homogenize temperature distribution: ±2°C (<1%) over 10cm
- Temperature is high enough: need ≈650°C in PITZ experiment

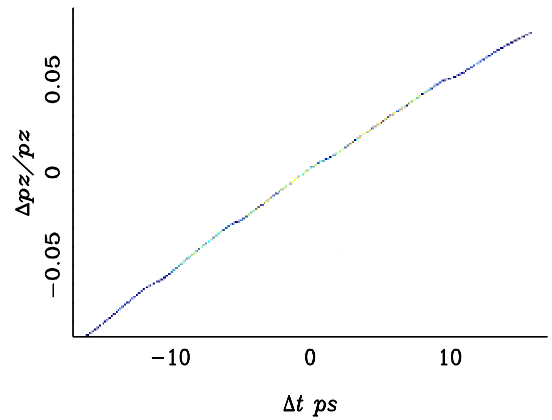
Multi Bunches: High Transformer Ratio

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

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

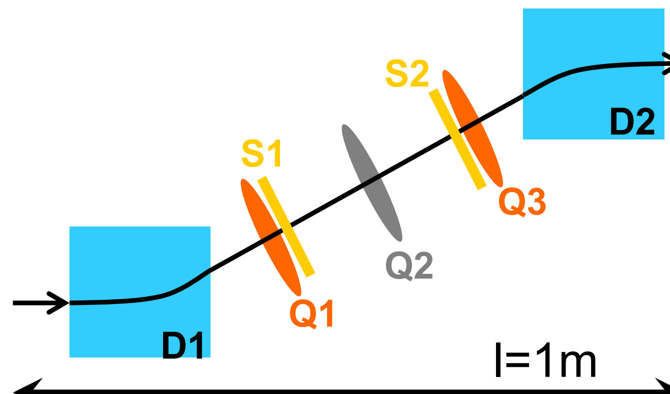
ASTRA simulations through gun and booster up to z=5m

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

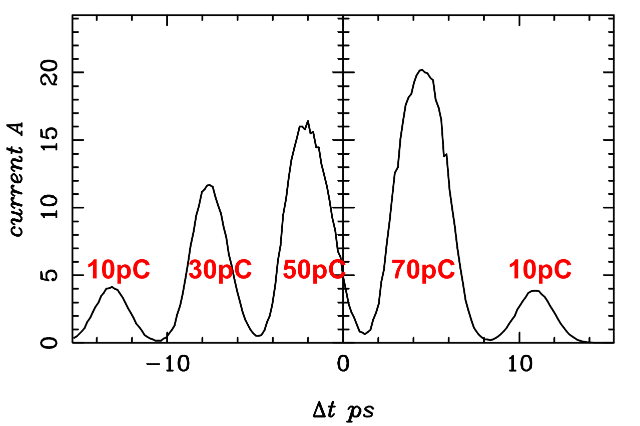


use **Elegant** for matching
and the dogleg design (ongoing)

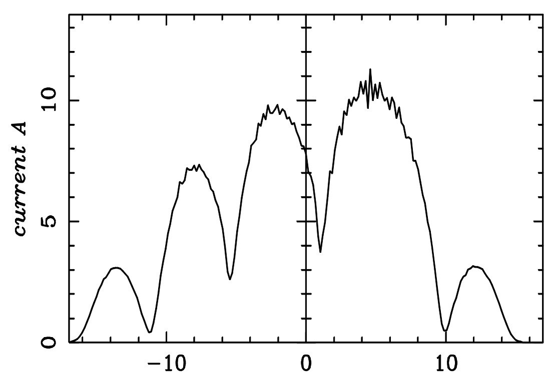
BC layout:
compression factor C = 4
R_{56} = 0.15
Total length l = 1m
dipoles: r = 0.6m, α = 60 deg



Longitudinal laser profile at the cathode



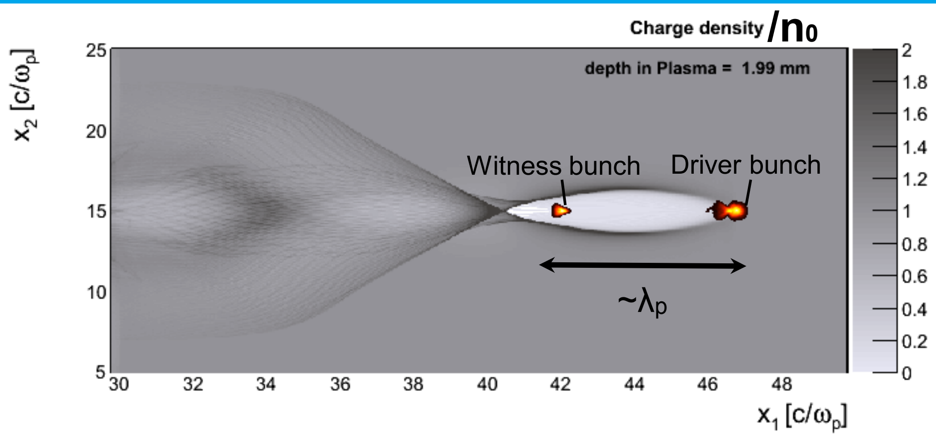
Longitudinal phase space at z=5m



Design with 2 doglegs (↑↓) on the way

Simulation by Anne Oppelt

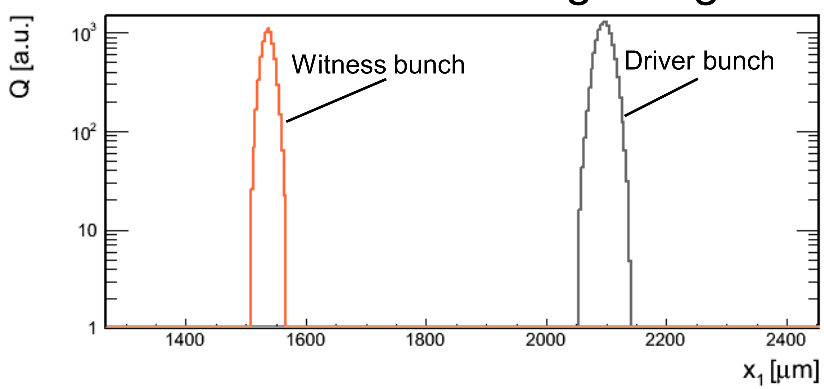
Very Preliminary Results: Needs Optimization



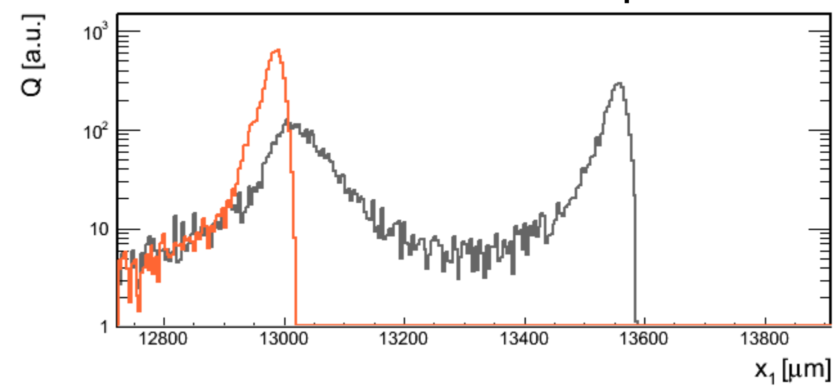
The witness bunch falls in the region where the wakefield is maximum.

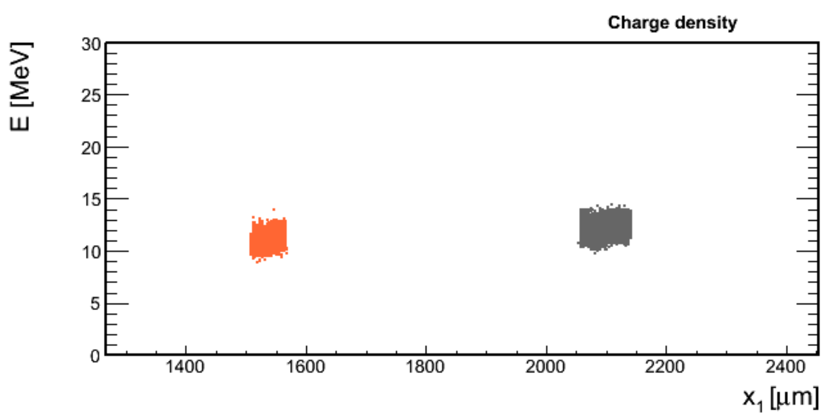
In approx. 1 cm of propagation in the plasma, a fraction of the electrons in the witness bunch double their energy.

Bunches at the beginning:

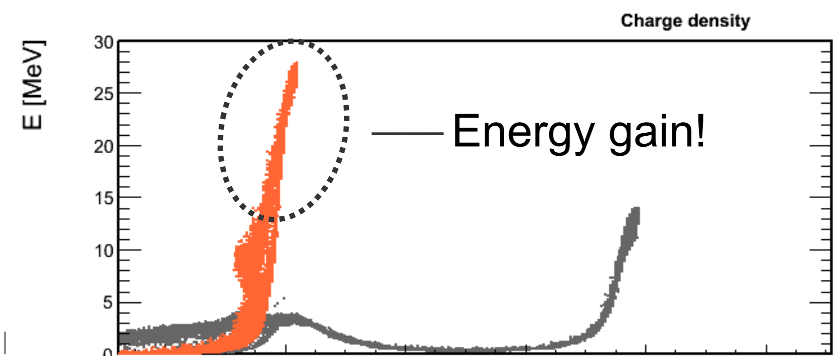


Bunches after 1 cm in plasma:





Gross |



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

> Backup

Transformer Ratio (TR)

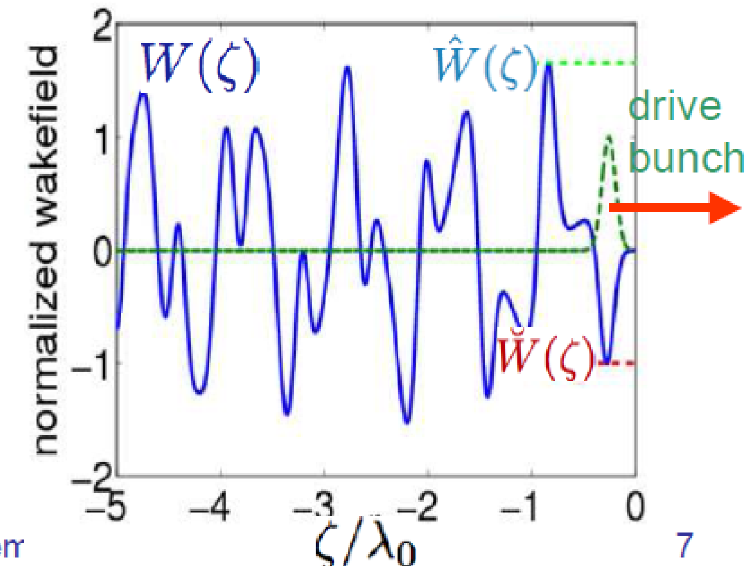
- TR defined as $\mathcal{R} \equiv \frac{\hat{W}(\zeta)}{\breve{W}(\zeta)}$

  $\hat{W}(\zeta)$: accelerating field behind bunch

  $\breve{W}(\zeta)$: decelerating field within bunch

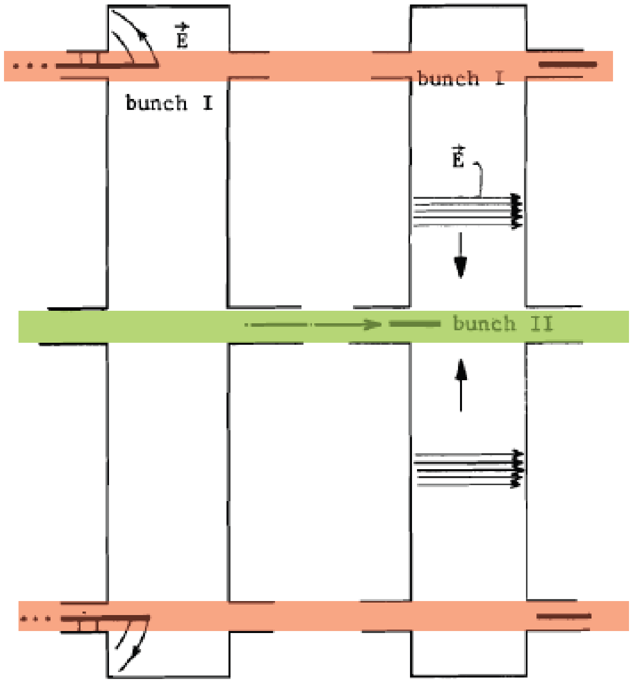
- Figure of merit for beam driven-acceleration
  - High-TR desired for multistage acceleration,
  - At low energies high TR increase interaction length.

- For a bunch with symmetric current profiles $\mathcal{R} \leq 2$ (fundamental beam loading "theorem")

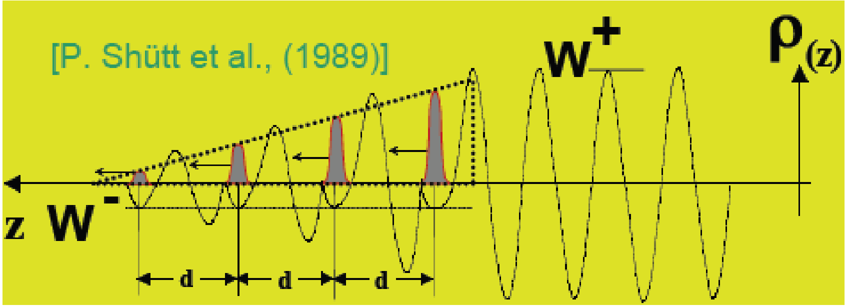


TR enhancement

- Non-collinear configurations:
  - Two-beam accelerator,
  - Two-beam in same structure (e.g. DESY hallow beam config.)
- Use of different species:
  - Wakeatron [A. Ruggiero, 1985]: drive bunch is a proton beam (adapted to plasma wakefield acceleration recently!)

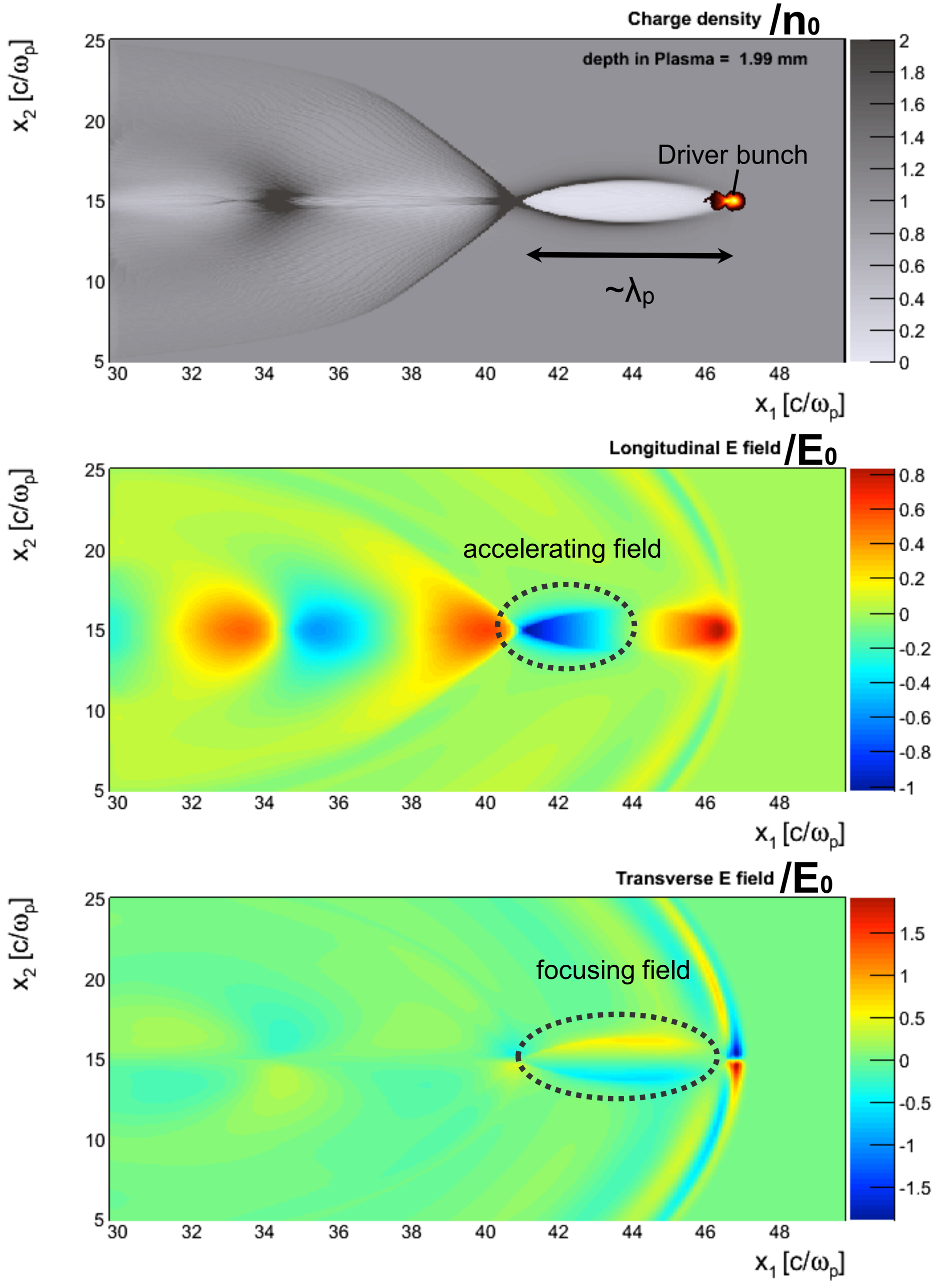


[G. A. Voss, Th. Weiland (1982)]



- Bunch train:
  - OK in the GHz regime
  - Difficult when dealing with THz structures
- Tailored bunch current profile:
  - Asymmetric bunch

Simulation of Beam-driven Plasma Wakefields



PITZ's beam layout after the BC (0.034T)

2-heads shape
separated by ~ 550μm

1. Driver bunch

Q=526 pC, σ_z=15μm, <E>=13 MeV

2. Witness bunch

Q=158 pC, σ_z=10μm, <E>=12 MeV

Plasma

$n_0 = 2\times10^{15}$ e/cm^3

$\omega_p = (4\pi n_0 e^2/m)^{1/2} = 2.5\times10^{-3}$ fs^{-1}

$\lambda_p = 2\pi c/\omega_p = 750$ μm

$E_0 = mc\omega_p/e = 4.3$ GeV/m

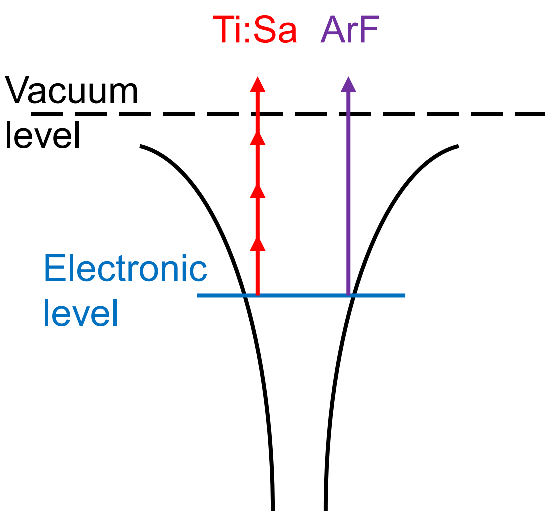
The driver bunch enables a longitudinal wakefield of 4.3 GeV/m approx. λ_p behind the beam's front.

Simulation by Alberto Martinez de la Ossa

Ionization Processes

Low field

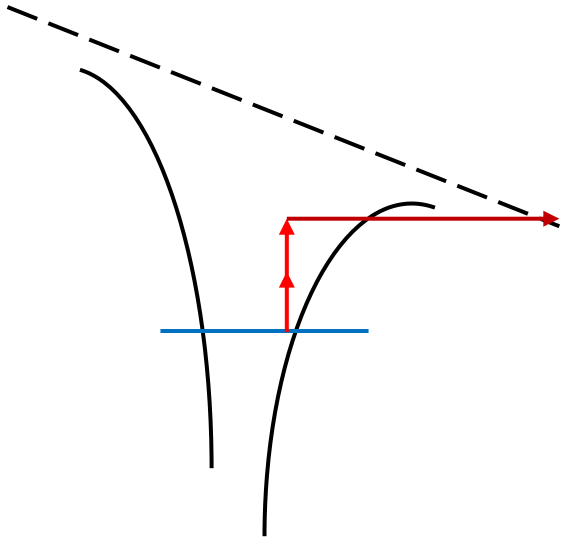
1. (Multi) photon absorption



$\chi^{(4)}$ – process for Li and Ti:Sa laser (Low probability)

High field

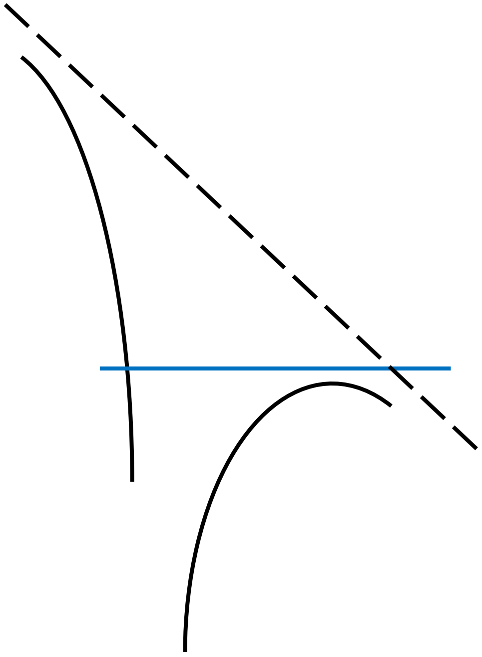
2. Tunneling ionization



Described by ADK theory (Exponential law)

Highest field

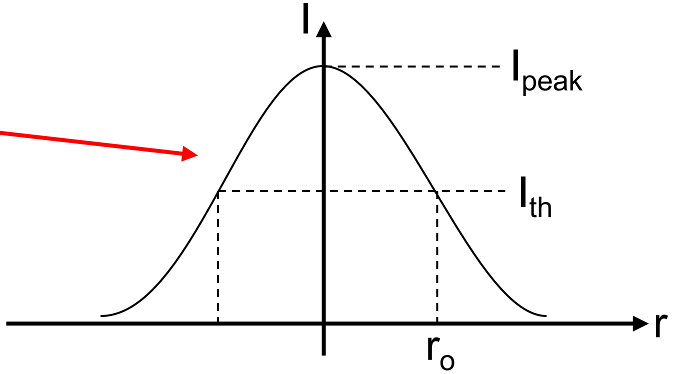
3. Barrier suppressed ionization (BSI)



Full ionization possible

Estimation of Ti:Sa Laser Peak Power

- Laser power needed for ideal case (uniform power density over lateral and longitudinal channel dimensions and DC case): $P_{id}=I_{th}\pi r_0^2$
  - Channel radius: r_0 ; BSI Ionization threshold I_{th} ($3.4*10^{12}$ W/cm^2 for Li)
- Power increased by ≈24
  - Lateral distribution: factor ≈2
  - Longitudinal: factor ≈2
  - Short pulse: factor ≈3
  - Transport loss etc.: factor ≈2



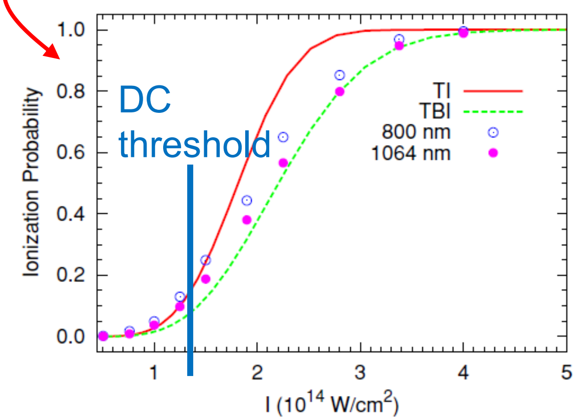
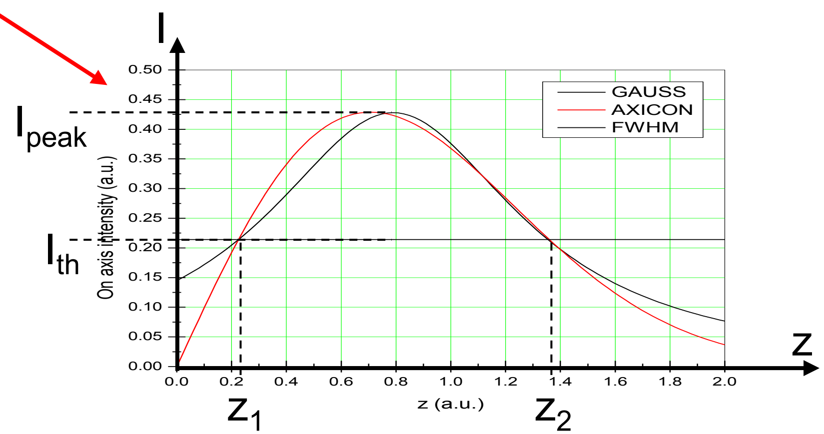


Figure 5. Ionization probabilities of hydrogen atoms in a 25 fs pulsed laser with varying peak intensities.

from: Tong et al., *J. Phys. B* **38** (2005) p. 2593



Ionization Energies: Single Photon and Field Ionization

- From Z. Najmudin's talk at PDPWA workshop (Munich, Dec 1st 2011)
  - Energy required to completely ionize a 1m long, 1mm^2 plasma channel (Single Photon)
  - BSI Intensity: Threshold intensity for complete ionization (Field Ionization)

Medium	ε_{ion} (eV)	Z	λ_{ion} (μm)	harmonic n_{800}	Energy required (mJ)	BSI Intensity (Wcm^{-2})
H	13.6	1	0.0912	8.8	17.11	1.37E+14
Li	5.39	1	0.2300	3.5	6.78	3.38E+12
Li+	75.6	2	0.0164	48.8	95.13	3.27E+16
Cs	3.89	1	0.3187	2.5	4.90	9.16E+11
Cs+	23.15	2	0.0536	14.9	29.13	2.87E+14
Ar	15.8	1	0.0785	10.2	19.88	2.49E+14
Ar+	27.6	2	0.0449	17.8	34.73	5.80E+14
N	14.5	1	0.0855	9.4	18.25	1.77E+14
N+	29.6	2	0.0419	19.1	37.25	7.68E+14

Additional use of Ti:Sa laser

Problem

- Measurement of density fluctuation in a plasma for PWA at PITZ

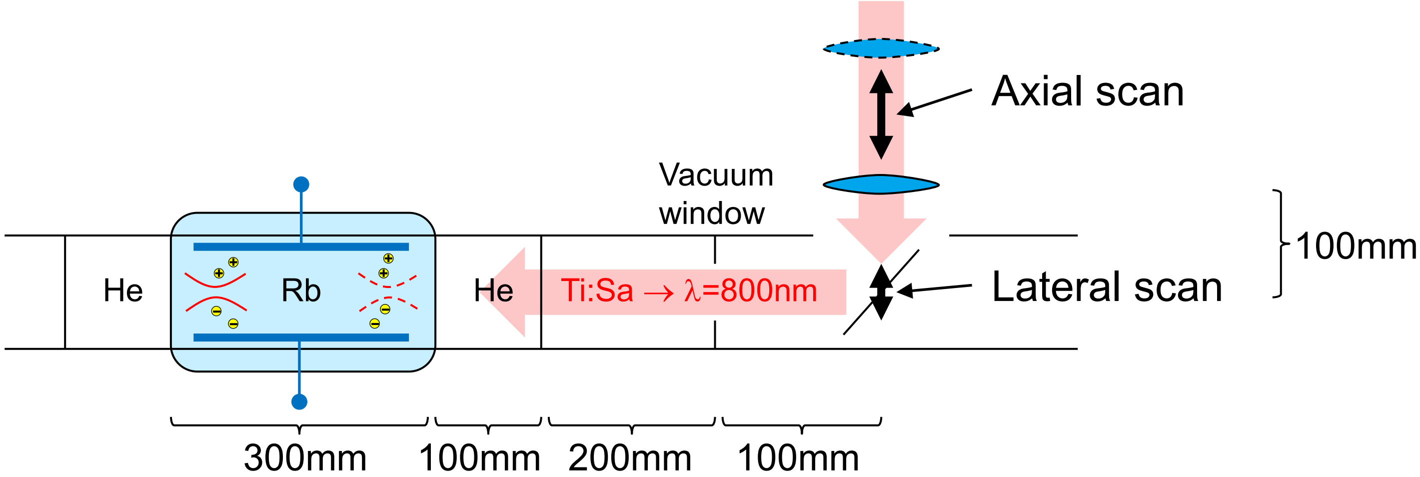
Facts

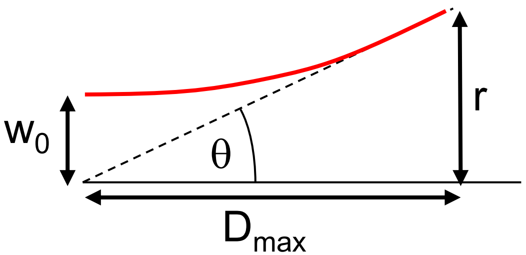
- Alkali metal vapor (e.g. Rb) with density of about 10^{15} cm^{-3}
- Basic Idea from Markus Drescher: Focus laser within gas to ionize small volume, then collect ions

Idea

- Use Ti:Sa laser for this measurement and ionization for PWA: gas density = plasma density
- Focus laser coaxially into gas volume so that field ionization threshold is exceeded only in small volume around beam waist – scan this focus around plasma cell
- Pick up ions with big electrodes, e.g. plates or wires: the electrodes do not need high resolution since that is done by the laser focus – no need for local detector

Setup Details / Back of the envelope Calculation





> Assume: Gaussian beam

- D_{max} = (300+100+200+100+100)mm = 800mm
- r = 5mm (half diameter of vacuum window – worst case: put at D_{max})
- $\rightarrow \theta_{max} = 6$ mrad
- Lateral resolution: $2w_{0,max} = 2\lambda/\pi\theta \approx 80\mu m$
- Calculation of axial resolution also leads to value <100μm

> High resolution measurement possible, could be evaluated at PITZ

Plasma Cell Assembly: Sketch

Design:
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