Studies for Particle Driven Plasma Acceleration at PITZ

Experiments planned utilizing PITZ

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Proton-Driven PWA Meeting
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HELMHOLTZ
ASSOCIATION

DESY

Contents

> Basics
> Unique positioning of Photo Injector Test Facility (PITZ)
> State of development of plasma cell
> Outlook: high transformer ratio

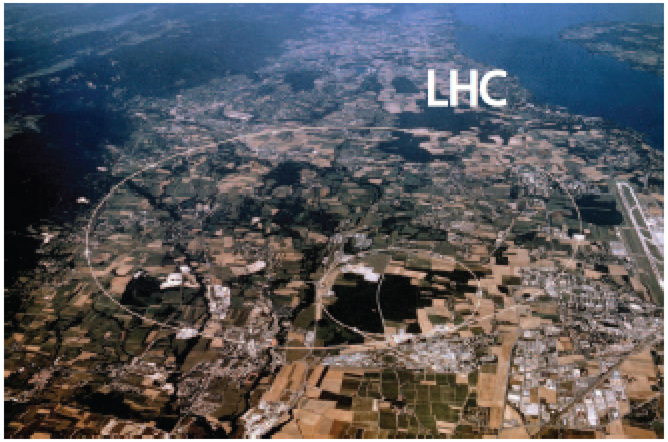
DESY, Location Zeuthen

- Former Institute for High Energy Physics in Zeuthen (Academy of Sciences of the GDR). Was merged with DESY on 1st January 1992
- 200 employees, of which 50 are scientists

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: $L_b \sim \lambda_p \propto n^{-1/2}$

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

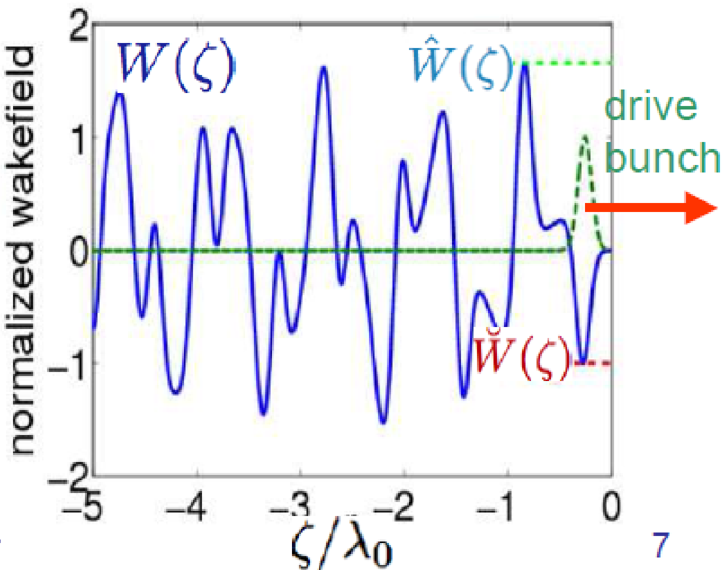
$\Rightarrow$ high accelerating gradient requires **short** bunches $\sigma_z \lesssim 100\ \mu$m
$\Rightarrow$ existing proton machines produce **long** bunches $\sigma_z \sim 10$ cm

- 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 ?

Transformer Ratio (TR)

- TR defined as $\mathcal{R} \equiv \frac{\hat{W}(\zeta)}{\breve{W}(\zeta)}$
  - accelerating field behind bunch
  - deccelerating 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")

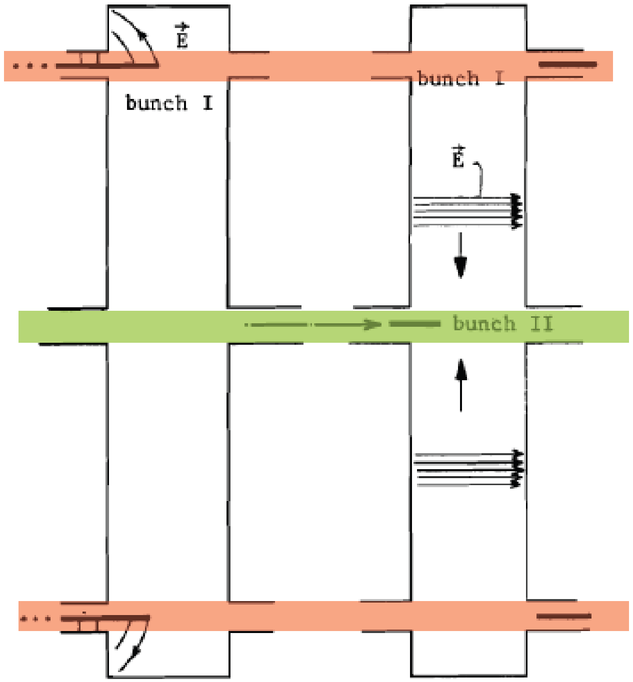


02-AUG-2011 P. Piot, MPY Sem 7

How to Increase the Transformer Ratio

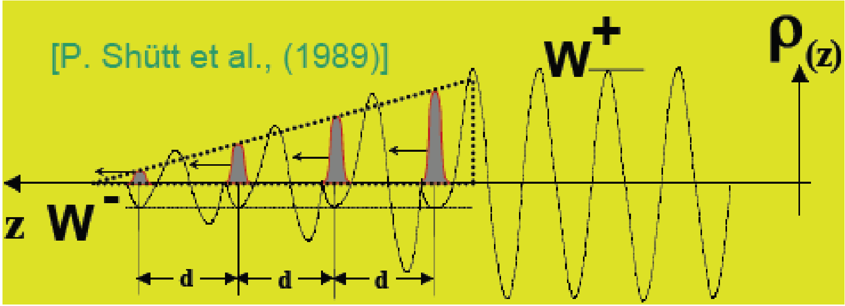
TR enhancement

- 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



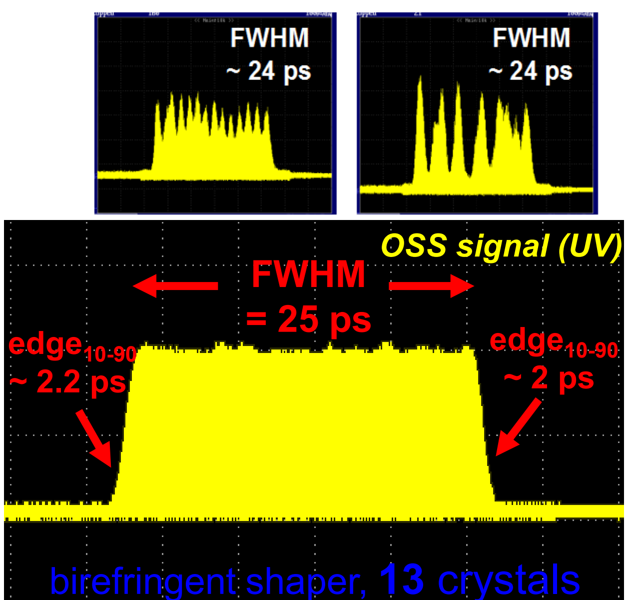
Why Experiments at PITZ?

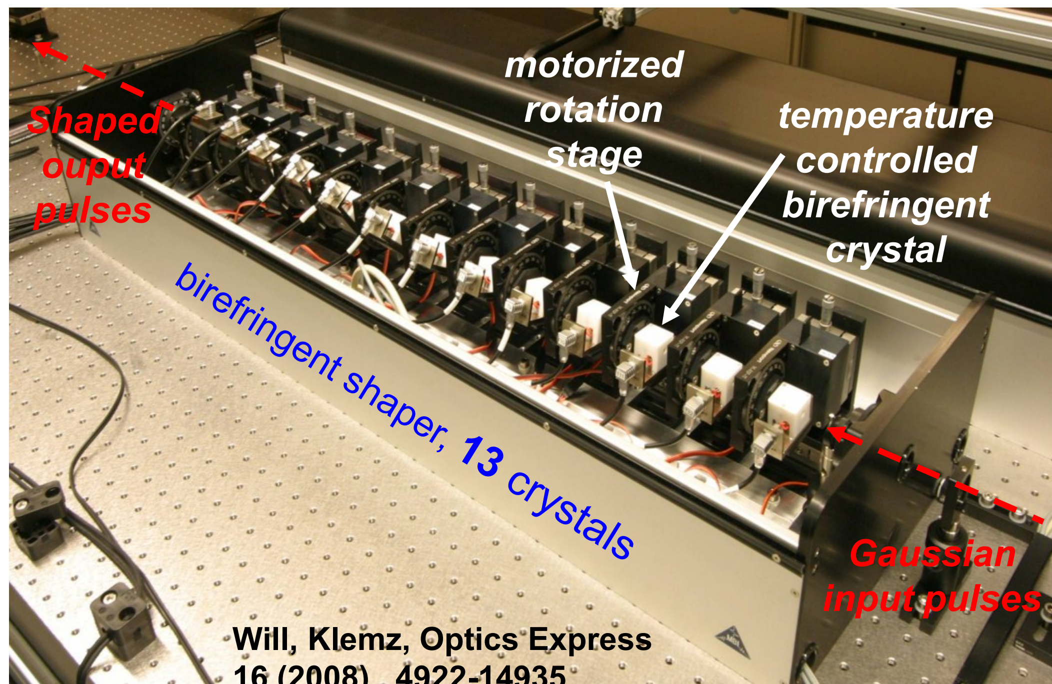
- Favorable circumstances
  - Pure R&D facility (no users)
  - Unique laser system (pulse shaper)
  - Well developed diagnostics (high resolution electron spectrometer, etc.); soon: transverse deflecting cavity + dispersive section for longitudinal phase space measurements
- Possible contribution from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

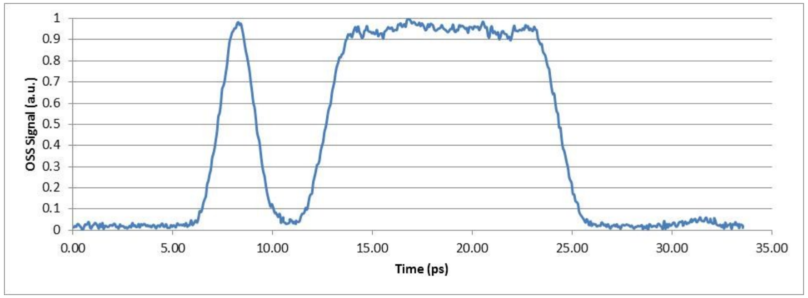
Simulated pulse-stacker



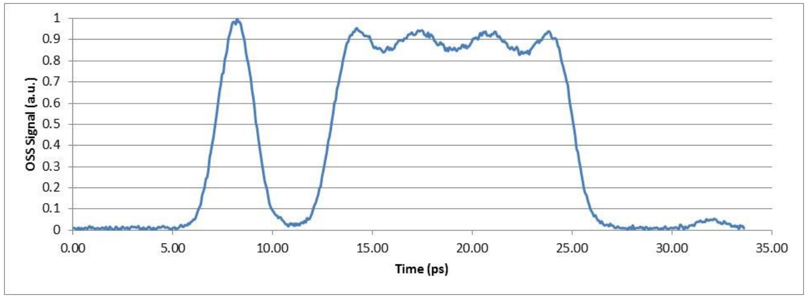


Experimentally Demonstrated Pulse Shapes

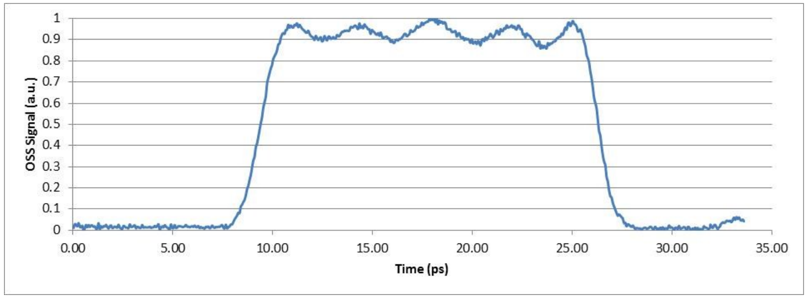
- Driver + witness bunch



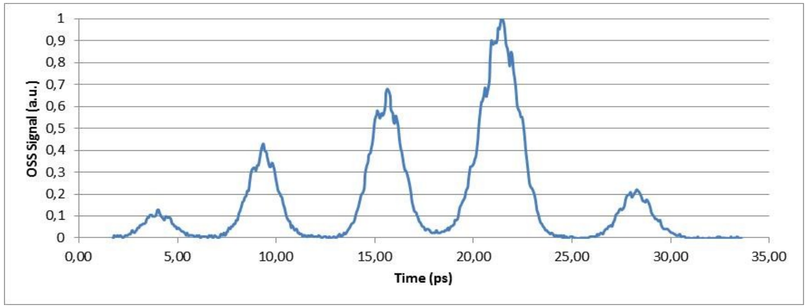
- Modulated driver + witness bunch



- Modulated driver

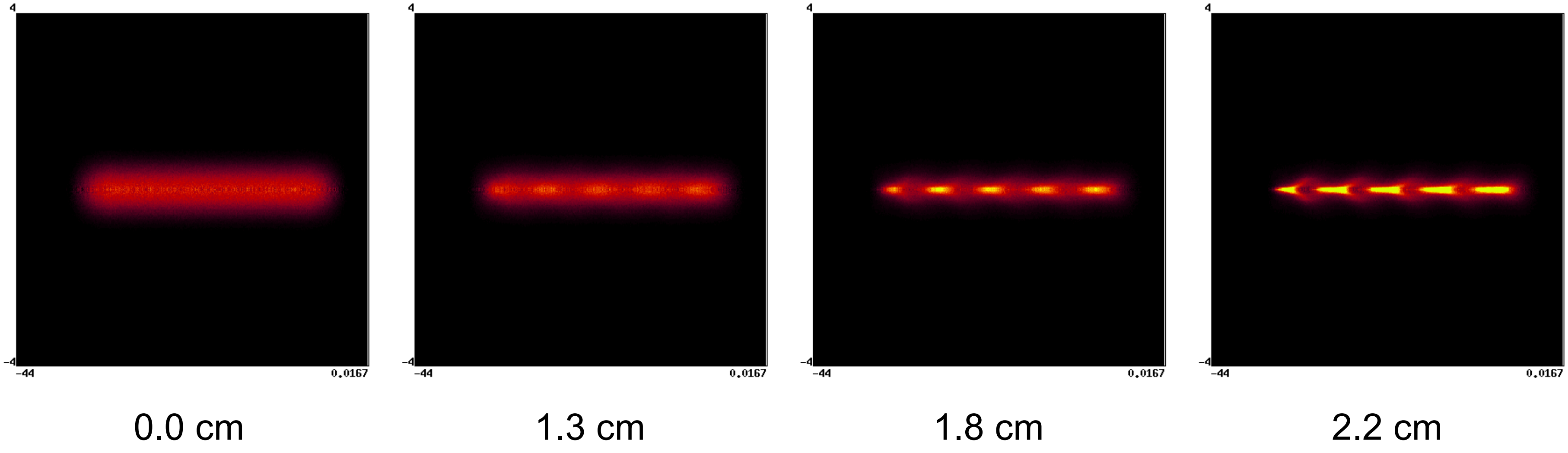


- Multi bunches



Simulation of Initial PITZ experiment

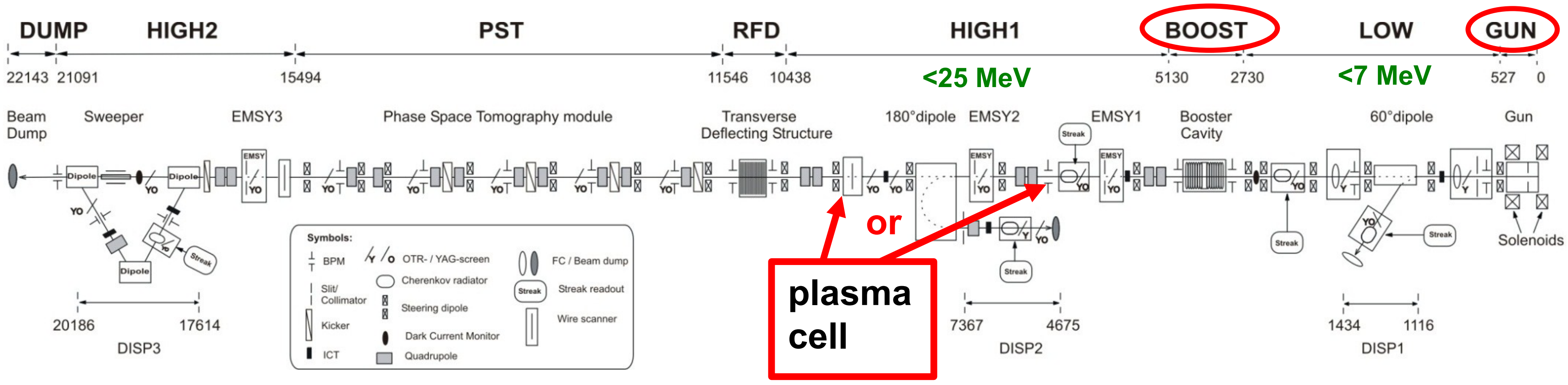
Simulation by Carl Schroeder



- Propagation of electron bunch in plasma: substructure is forming
- $\rightarrow$ Interaction of electron bunch with plasma
- Justification for experiment: Detailed characterization of substructures
  - Measurement of energy spectrum and longitudinal phase space depending on electron bunch (mean energy etc.) and plasma (density etc.) properties

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
- Current work: Beam dynamics simulations to determine which position is more favorable

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 (< 320nm), 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

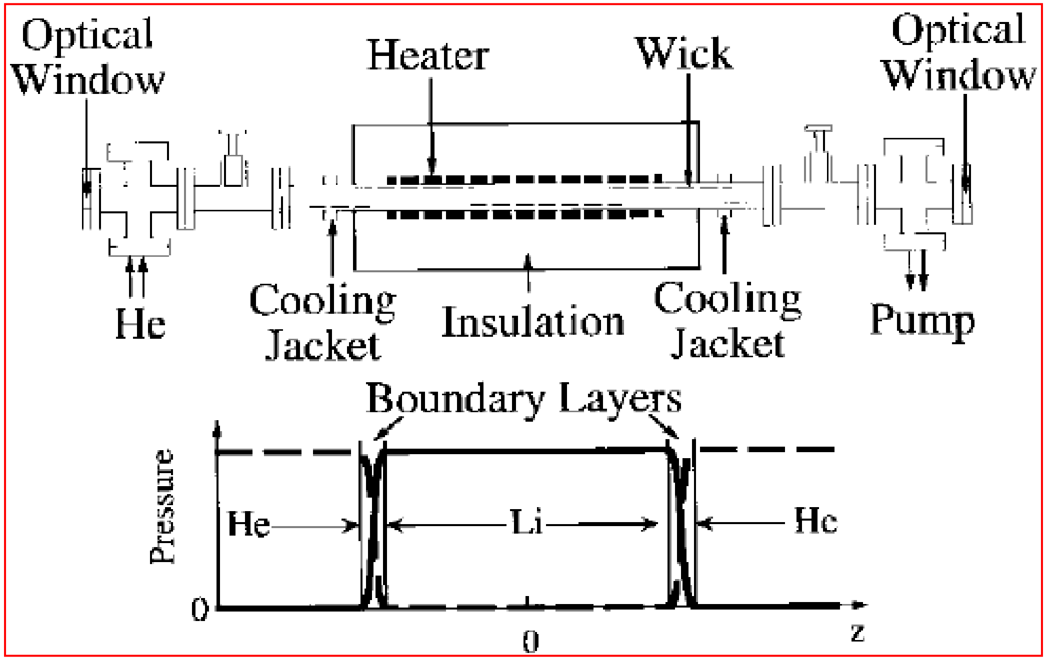
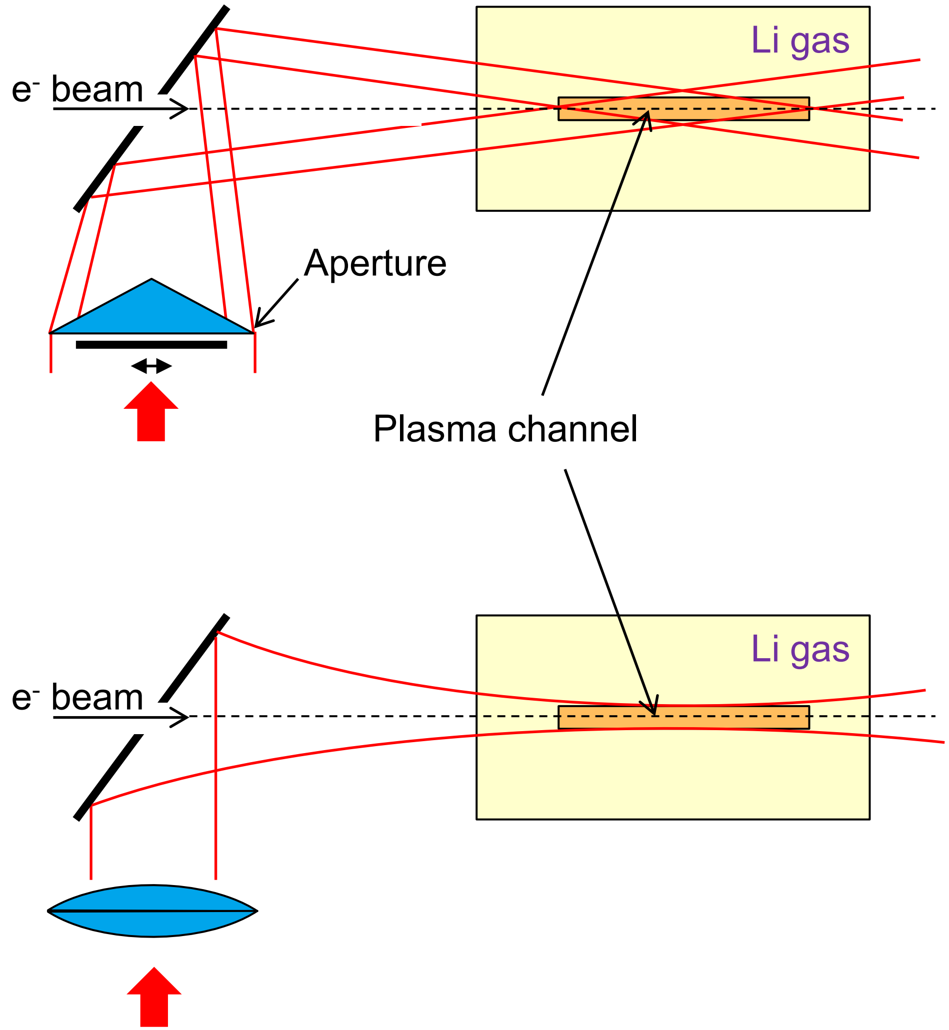


Figure from: P. Muggli et al. "Photo-Ionized Lithium Source for Plasma Accelerator Applications", *IEEE Trans. Plasma Science* **27** (1999), pp. 791-799

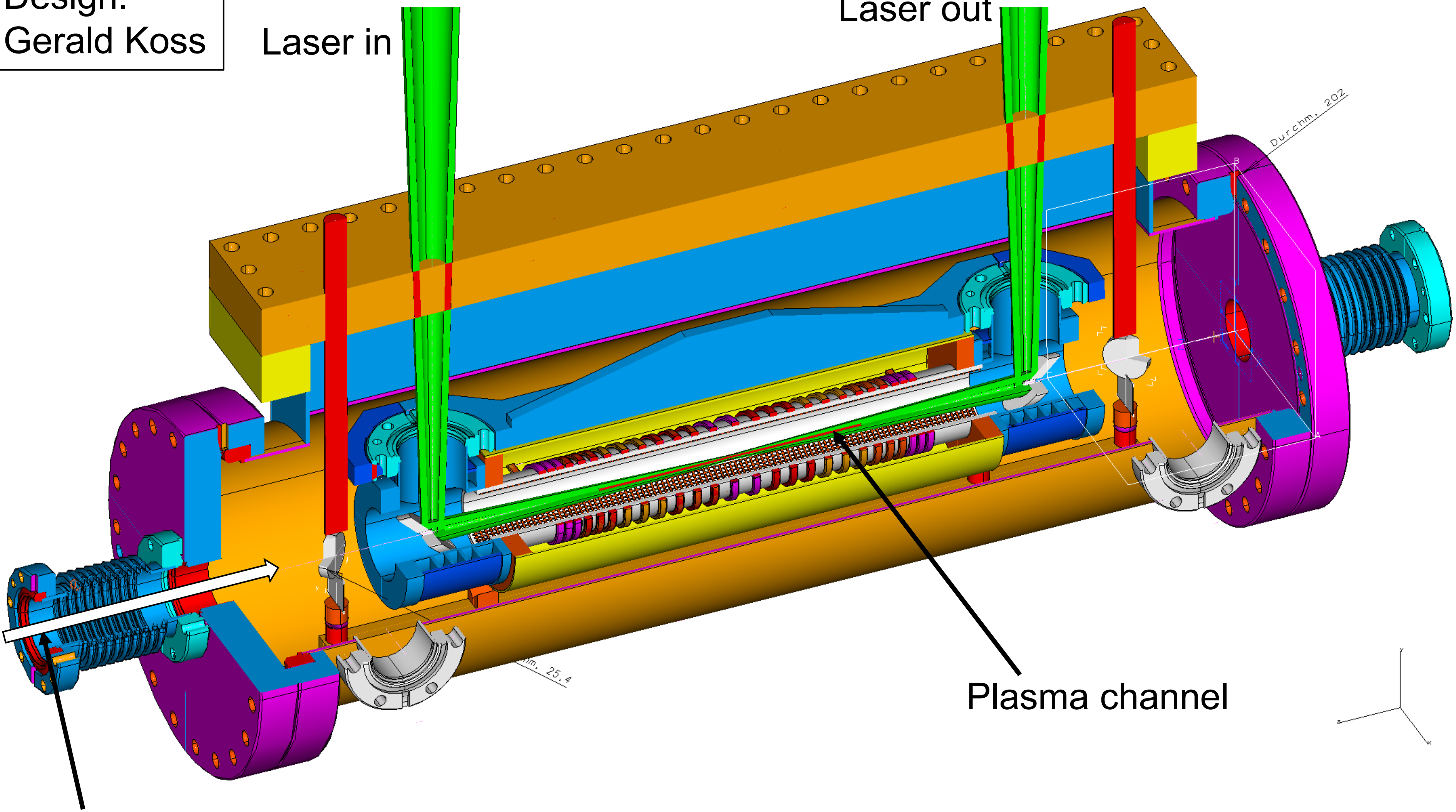
Optics for Laser Plasma Generation

- Axicon for homogeneous ionization profile
  - Adjustable aperture to define length of plasma channel
- Simple focusing lens
  - Length of plasma channel defined by laser intensity (has to be above threshold)



Plasma Cell Assembly: Sketch

Design:
Gerald Koss



Current Problem: Generation of Plasma Channel

- Want: plasma channel with adjustable length up to ≈10cm and 3…7mm diameter
- Geometry
  - Axicon with single mode input creates very thin (10s of μm) plasma channel for this length
  - Simple focusing lens could be used, but then begin and end of plasma channel is defined by gas transition (Li to He)
- Laser size
  - Ionizing such a big plasma channel needs a lot of power/energy
  - ArF laser: several 100mJ per pulse
  - Ti:Sa laser: several TW peak power
  - High power level makes laser beam transport difficult (filamentation in air, damaging lenses, mirrors etc.)

Multi Bunches: High Transformer Ratio

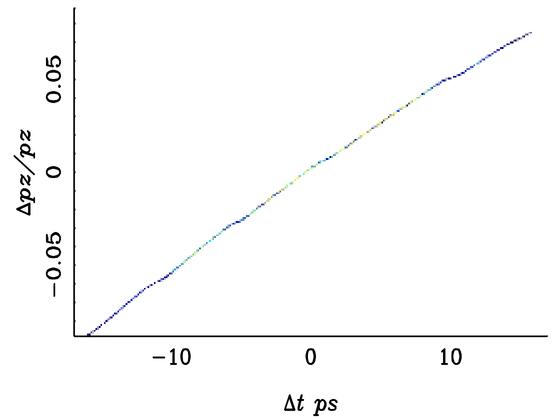
> Plasma Acceleration: e.g. 5 bunchlets within bunch → transformer ratio >2

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

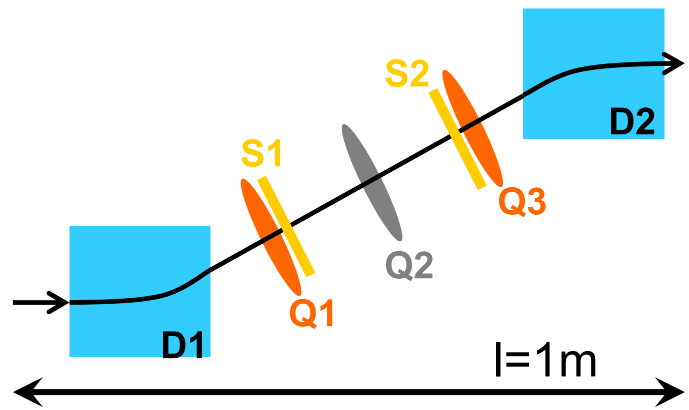
use **Elegant** for matching and the dogleg design (ongoing)

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

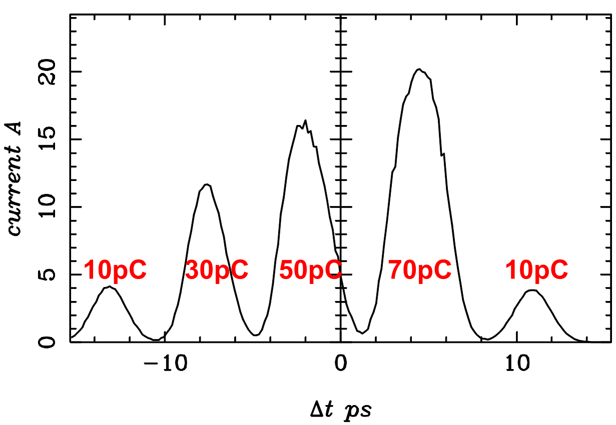


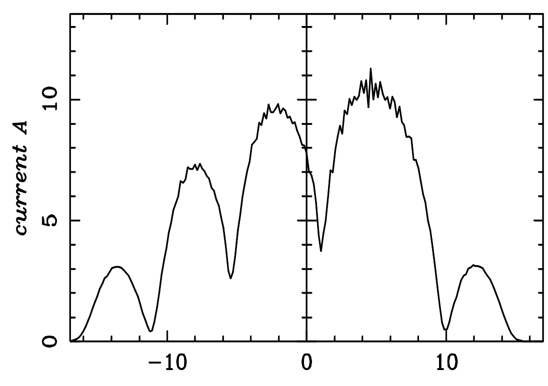
Longitudinal phase space at z=5m

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

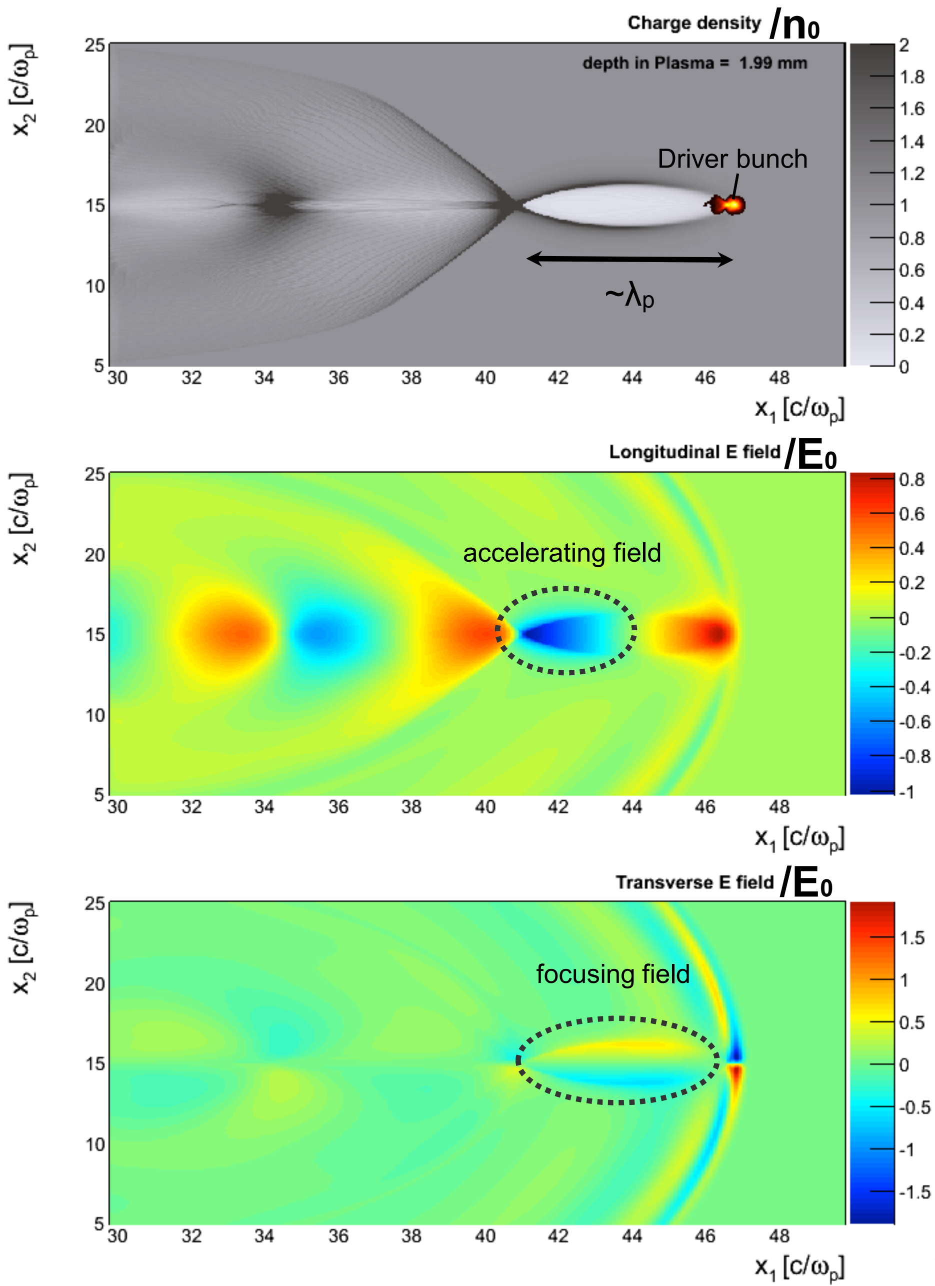




Design with 2 doglegs (↑↓) on the way

Simulation by Anne Oppelt

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

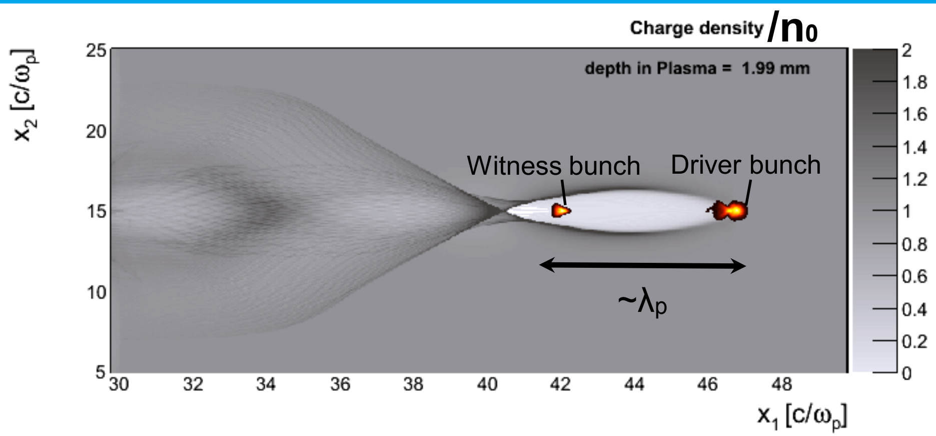
Plasma

$n_0 = 2\times10^{15}$ 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

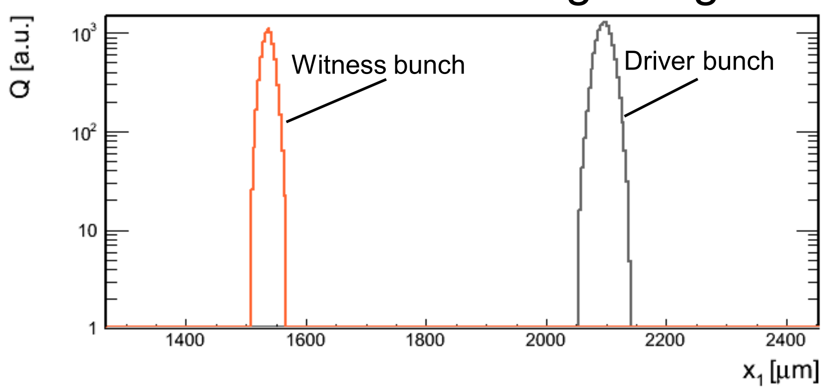
Very Preliminary Results: Needs Optimization

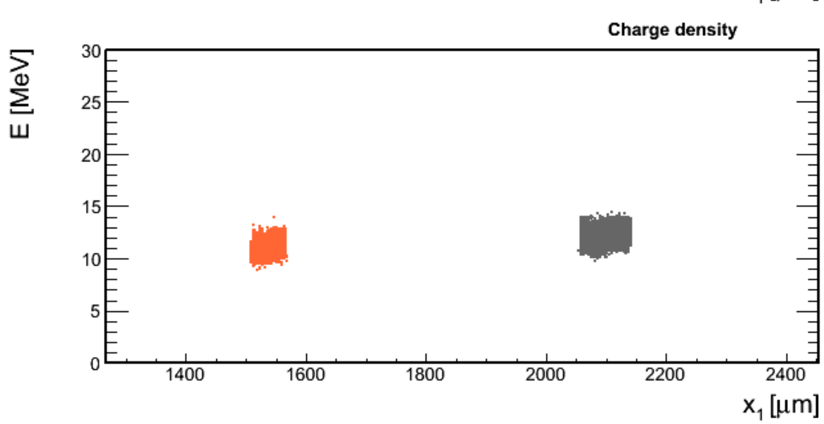


The witness bunch falls in the region where the wakefield is maximum.

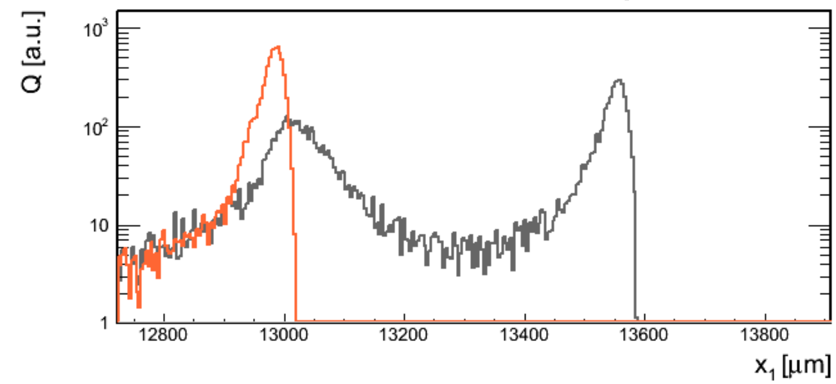
In approx. 1 cm of propagation in the plasma, a fraction of the electrons in the witness bunch double their energy.

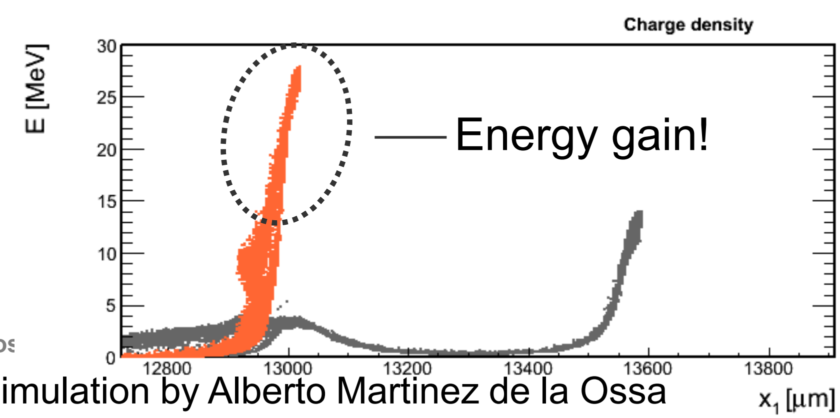
Bunches at the beginning:





Bunches after 1 cm in plasma:





Simulation by Alberto Martinez de la Ossa

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 with current setup
  - Energy gain with bunch compressor
- Current main problem: how to generate plasma channel