First Experimental Self-modulation Results

Matthias Groß for the LAOLA@PITZ team

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HELMHOLTZ ASSOCIATION

PITZ Photo Injector Test Facility Zeuthen

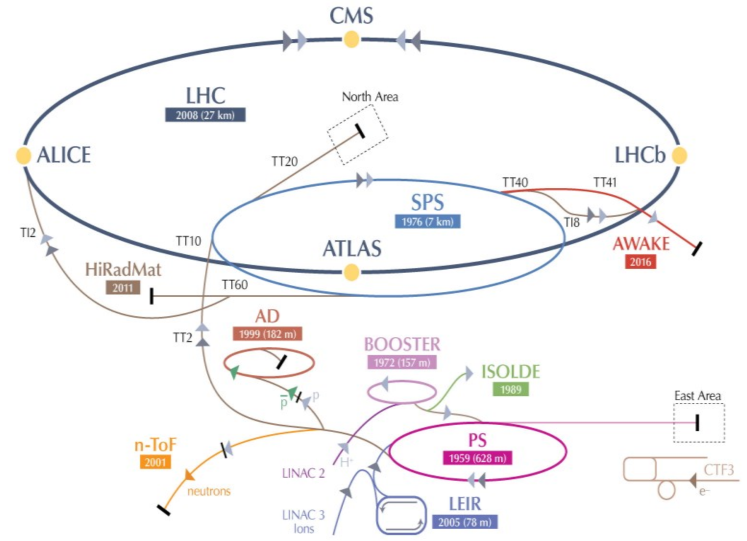
DESY

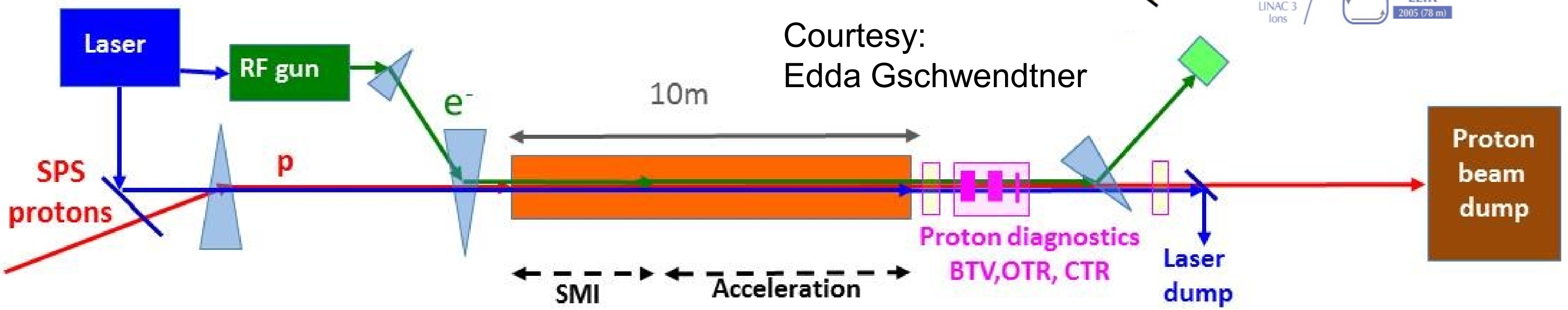
The LAOLA@PITZ Team

- Johannes Engel, Gerald Koss, Matthias Gross, Osip Lishilin, Gregor Loisch, Stefan Maschmann, Sebastian Philipp
- *Former Members: Gaurav Pathak, Dieter Richter, Marc Schinkel, Paul Weidemann, Valentin Wohlfarth*

EAAC Workshop 2015: Edda Gschwendtner – The AWAKE Facility at CERN

- Use high energy proton beams from SPS to drive plasma wave
- Convert proton beam energy to accelerate electron beam in single stage





Courtesy:
Edda Gschwendtner

- High accelerating gradient requires **short** bunches (σ_z less than 100µm)
- Existing proton machines produce **long** bunches (10cm)

Caldwell et al., Nature Physics (2009):

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

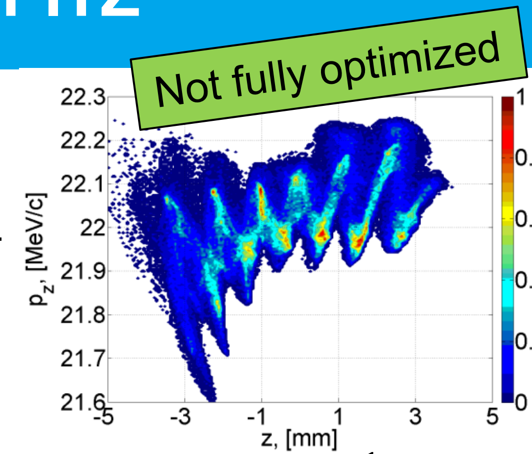
Self-modulation!

Simulated Self-modulation Experiment at PITZ

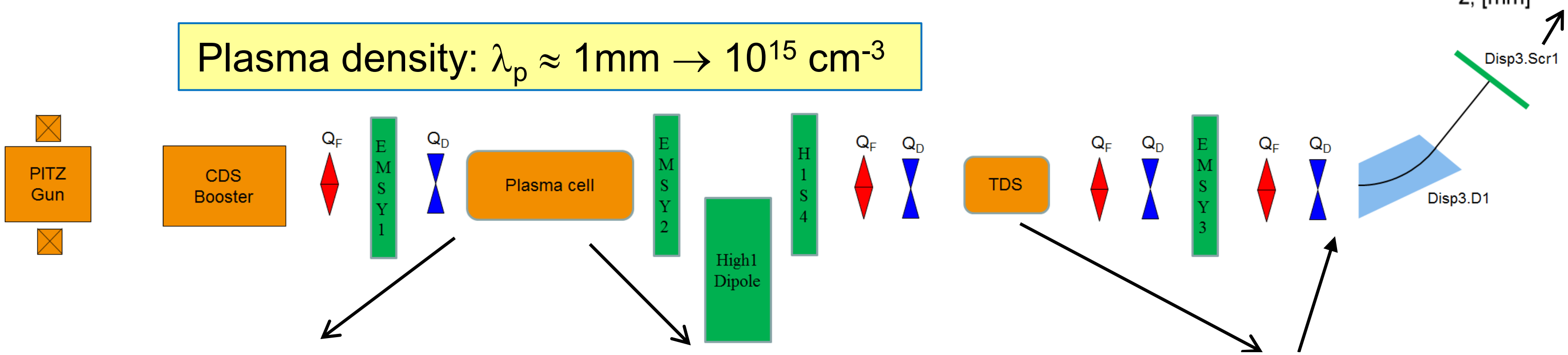
Longitudinal Phase-space studies

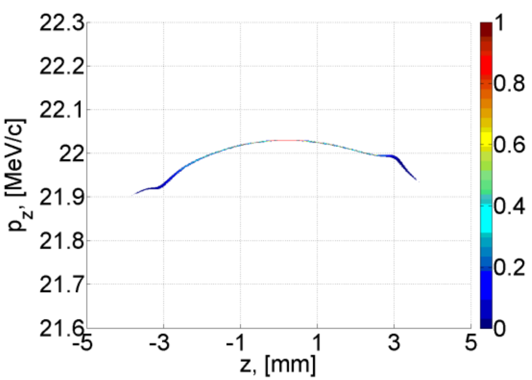
Simulations:
Martin Khojoyan /
Dmitriy Malyutin

Expected phase space

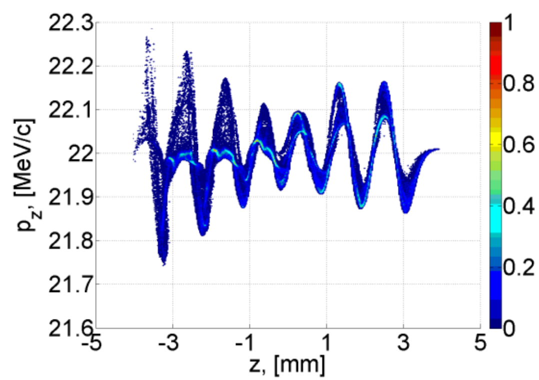


Plasma density: $\lambda_p \approx 1\text{mm} \rightarrow 10^{15}\ \text{cm}^{-3}$

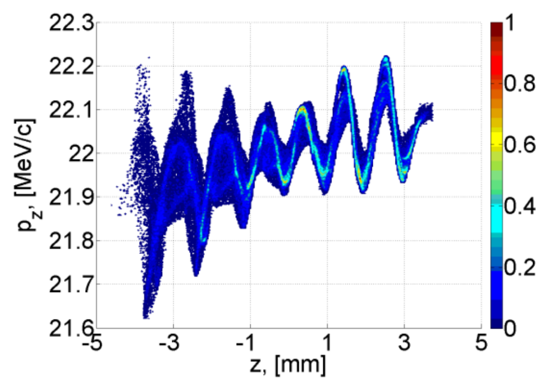




In front of plasma cell



After plasma cell
(assuming zero initial energy spread)

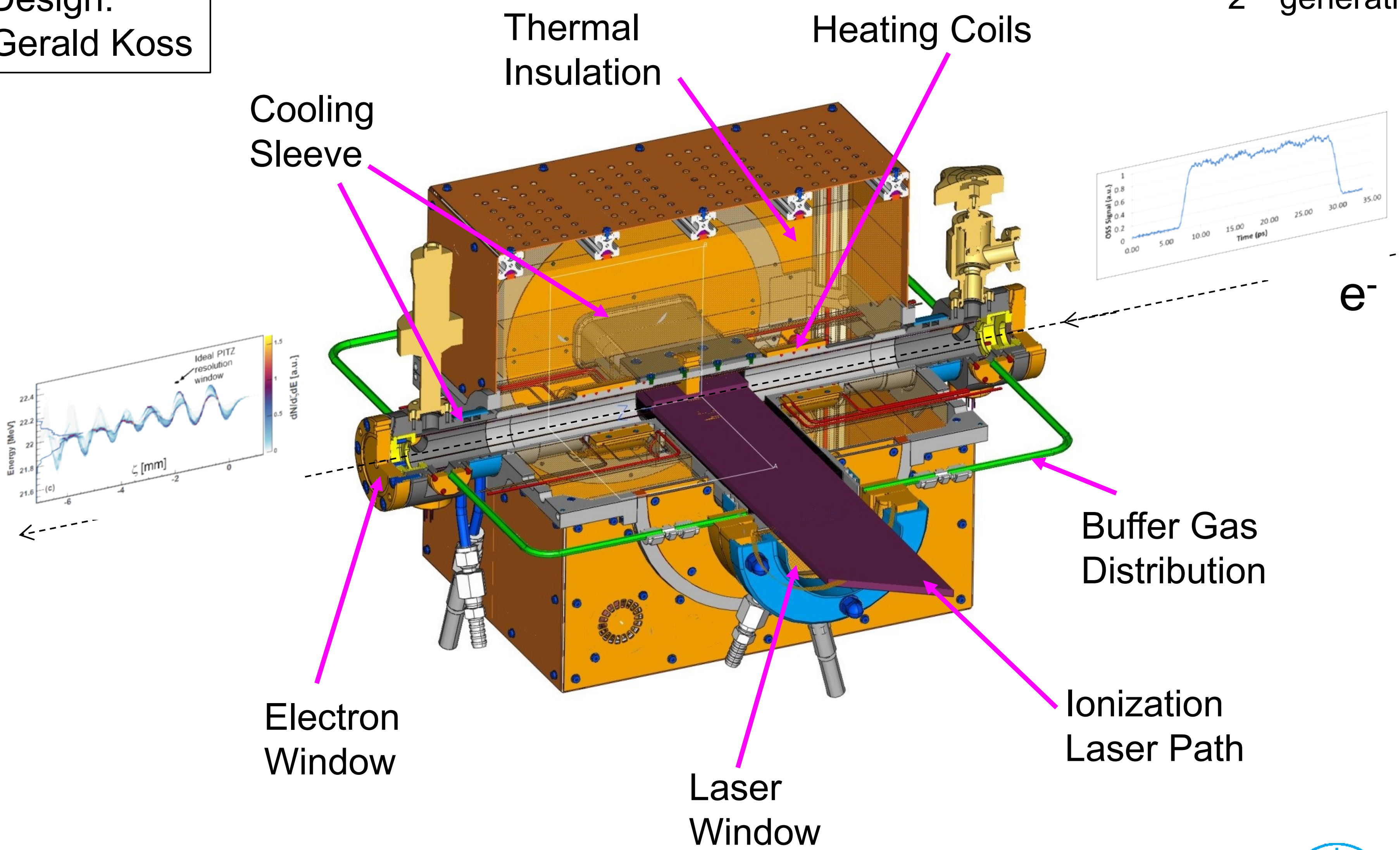


In front of dipole

Lithium Plasma Cell Design: Novel Cross Shape

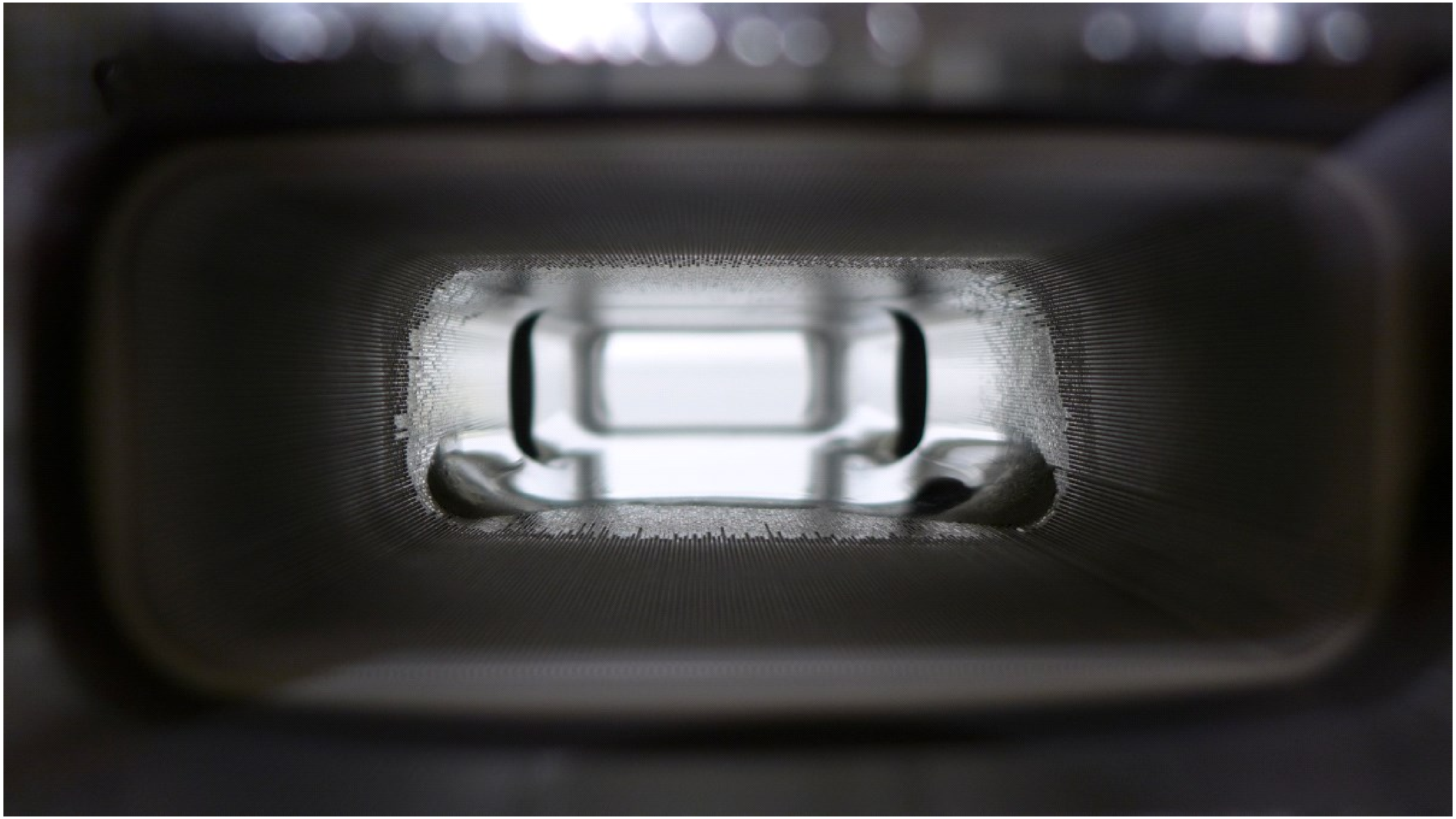
Design:
Gerald Koss

2nd generation



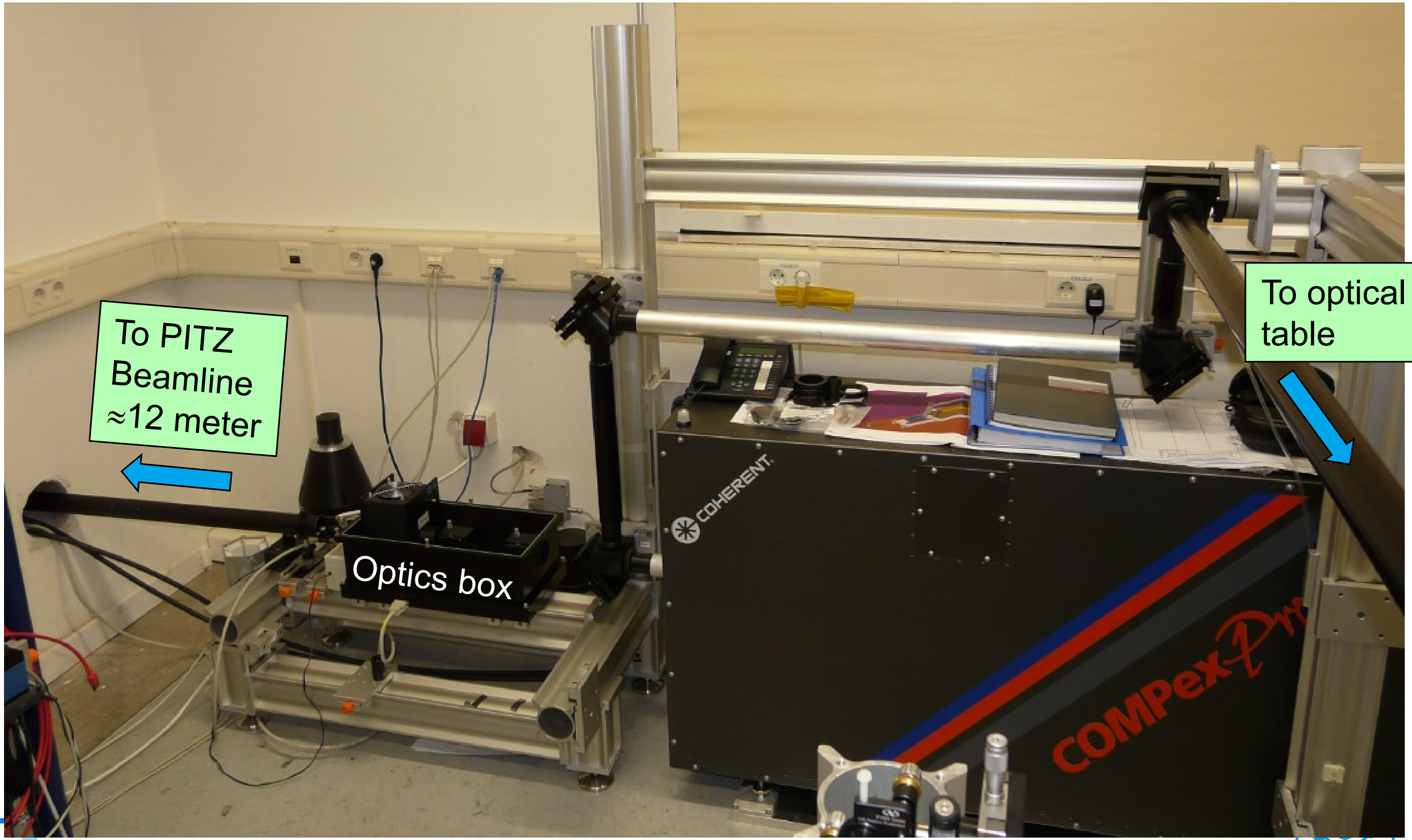
Specialty: Lithium Transport with Grooves

- Grooves were eroded into the steel block – here seen filled with Lithium



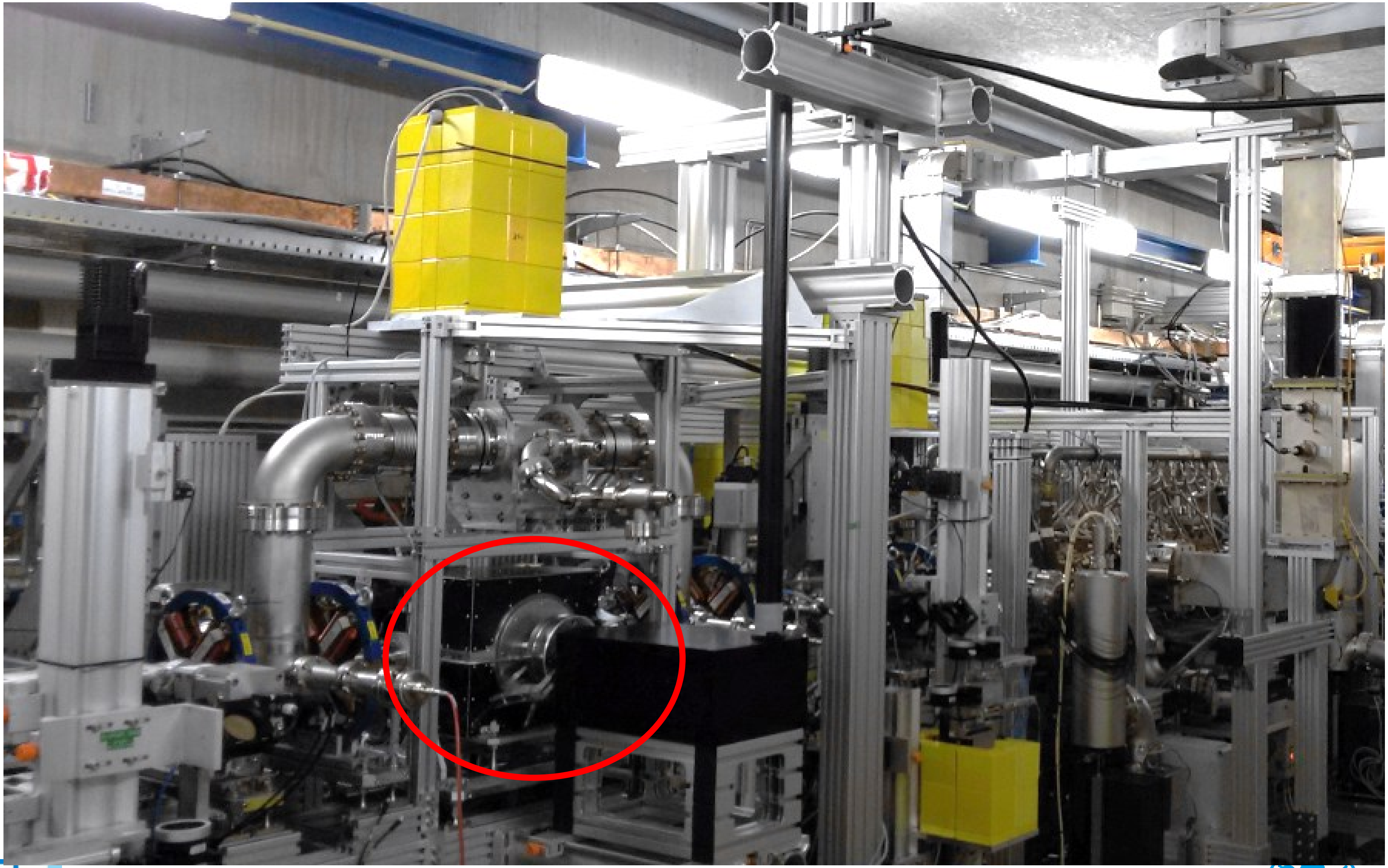
Ionization Laser (ArF Excimer Laser; 193 nm)

> Coherent COMPexPro 201*: up to 400 mJ / pulse; 10 Hz



* partially financed by Bernhard Hidding (UHH)

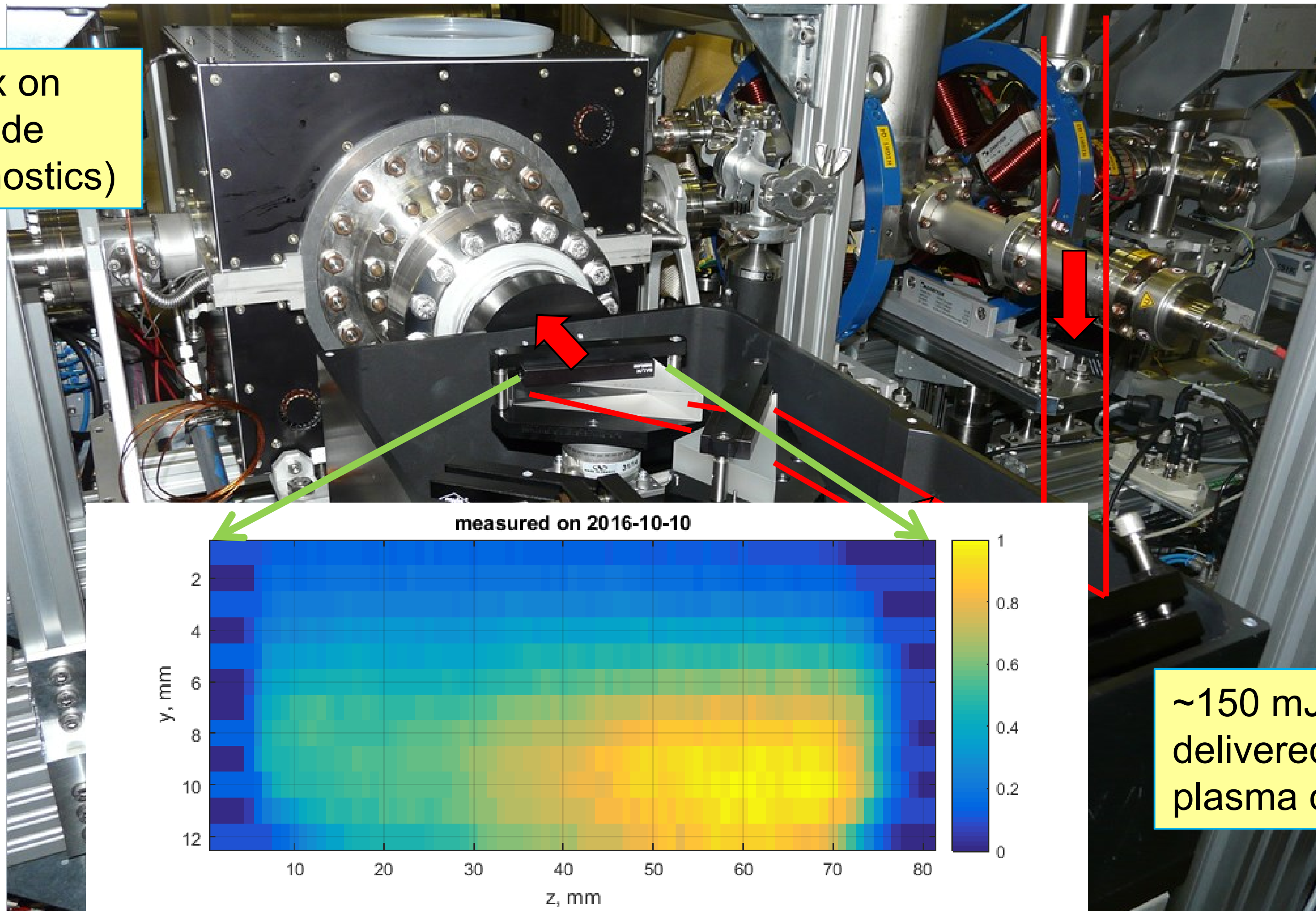
Lithium Plasma Cell Inserted Into PITZ Beamline



Plasma Cell with Ionization Laser Beam Expander

- Advantage: Well defined and adjustable plasma channel length
  - Option: Add filter to implement density ramps or other plasma profiles

Similar box on the back side (with diagnostics)

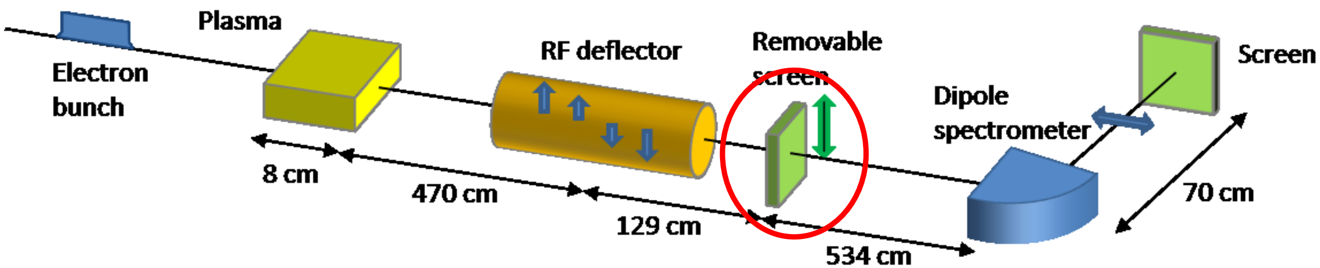


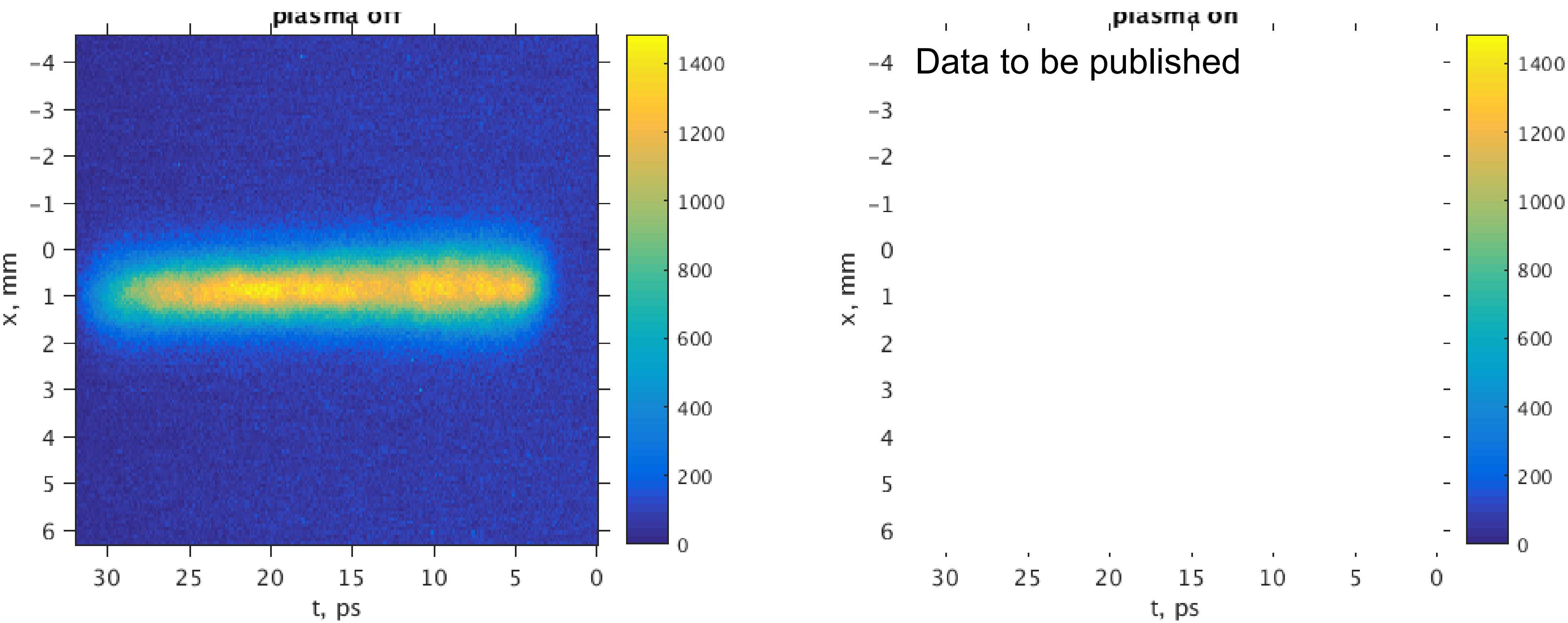
~150 mJ is delivered to the plasma cell

Experimental Conditions

- Gun/booster at MMMG phases
  - 6.5MW in the gun (6.5 MeV/c electron momentum) with 650μs pulse length
  - 3.0MW (**22 MeV/c electron momentum** downstream) in the booster with 200μs pulse length
- Electron bunches
  - Longitudinal: flat top with 26ps length and about **2ps rise and fall times**
  - Strong focusing into plasma cell: transverse size about 100 μm rms
- Plasma cell: lithium with argon buffer gas at 0.8 mbar, heated up to 700°C
- Ionization laser: ArF with about 150 mJ pulse energy delivered to plasma cell

Experimental Results: 1) Time Resolved Bunch





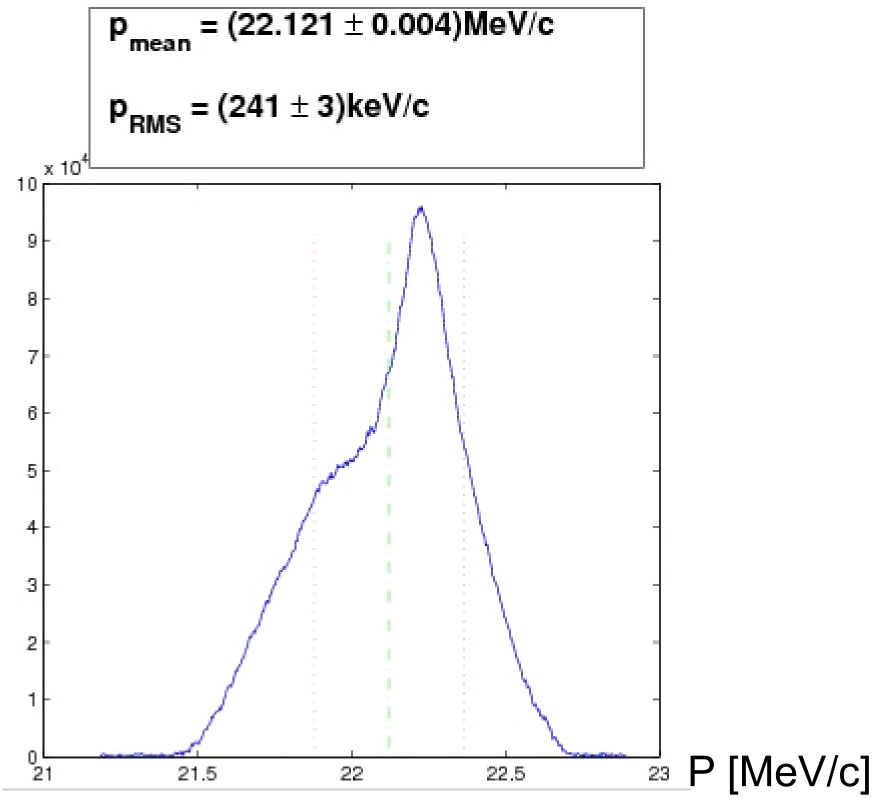
> Clear signature of self-modulation

Q=0.97 nC
Plasma density: $\approx 10^{14}$ cm^{-3}

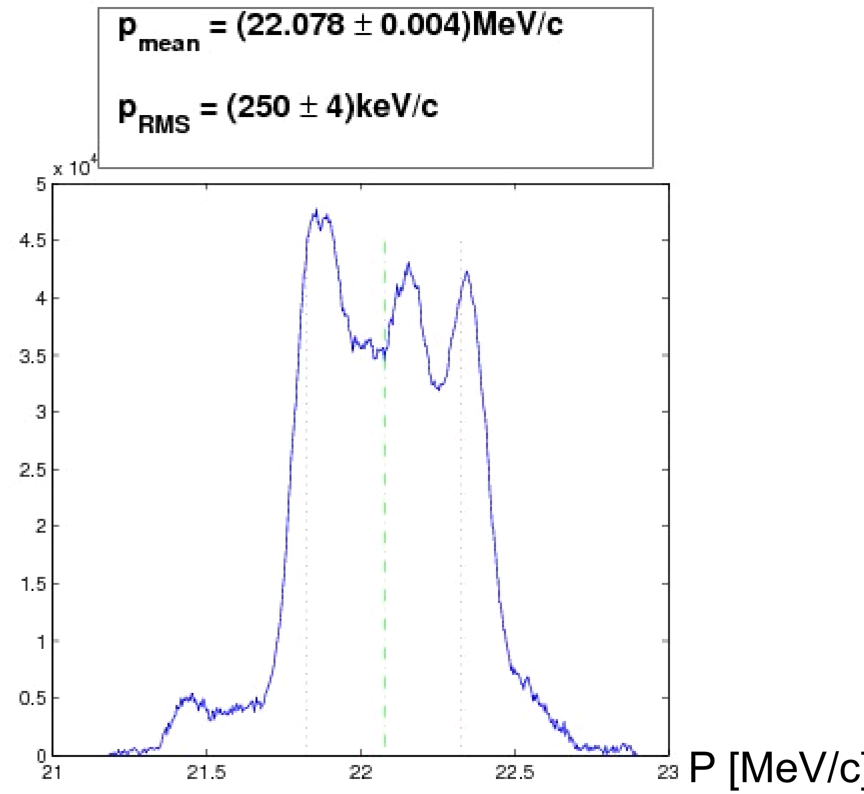
Experimental Results: 2) Energy Spectrum

Bunch charge: 970 pC
Plasma density: $\approx 10^{14}$ cm^{-3}

- Plasma off

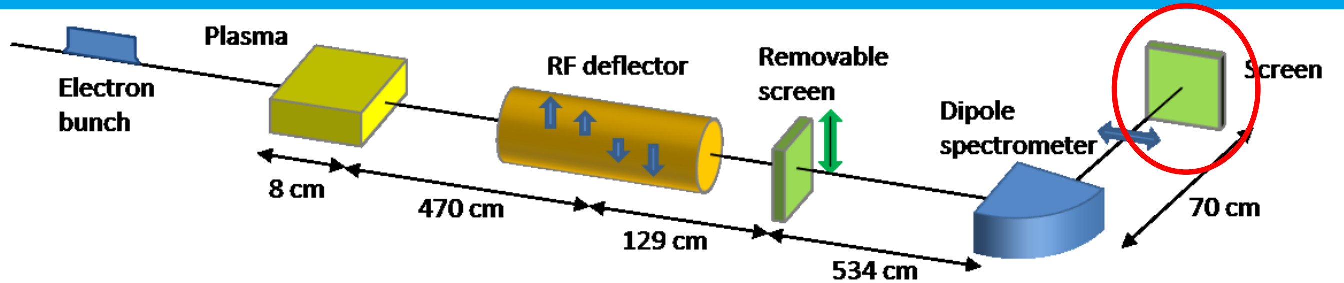


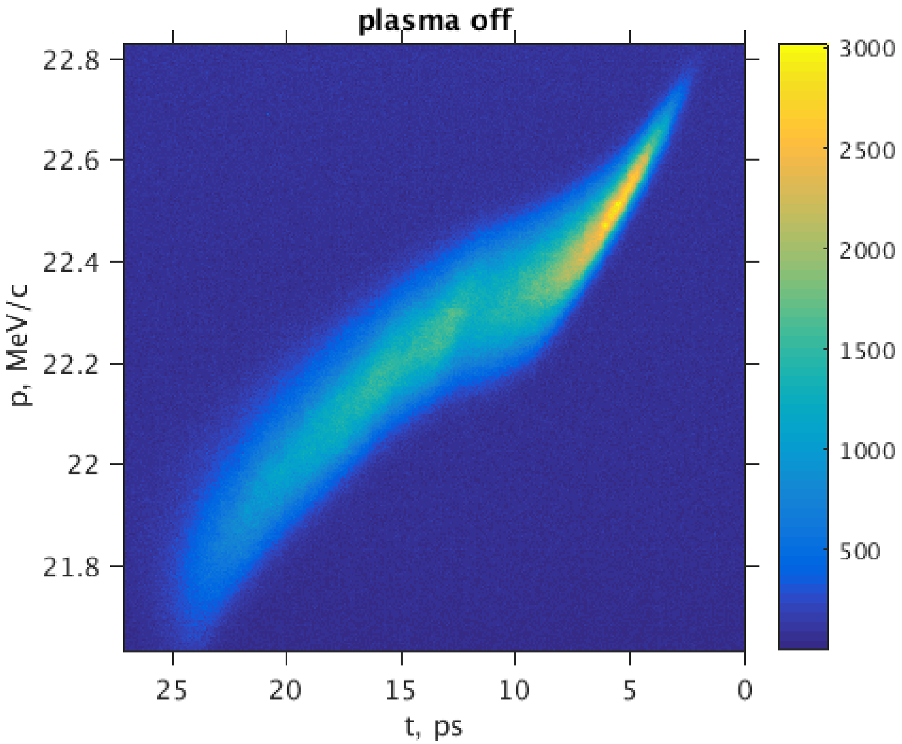
Plasma on

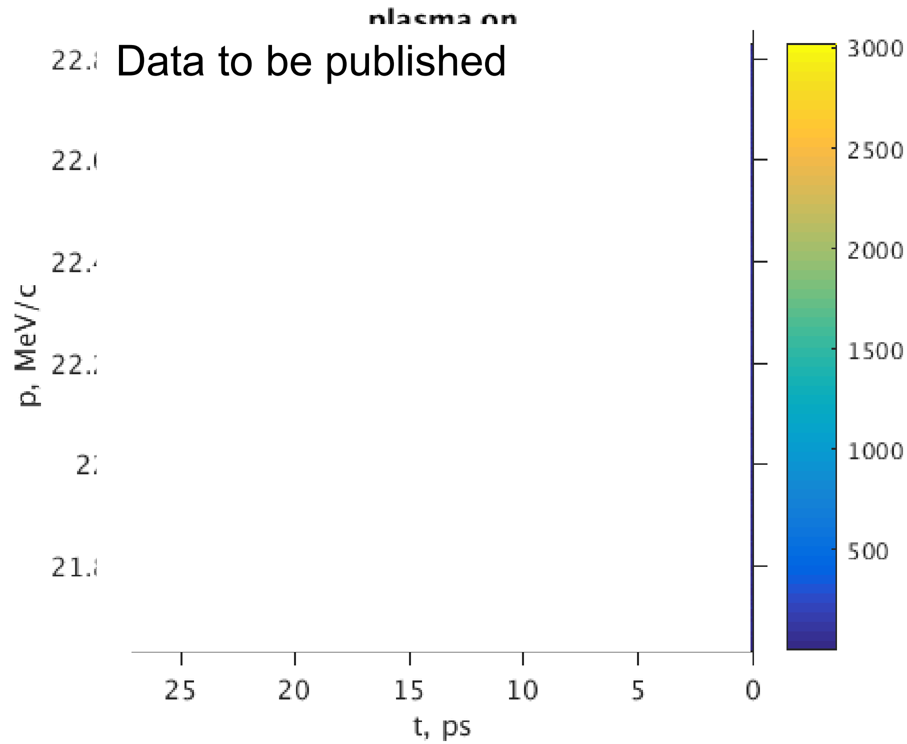


- Booster is slightly off-crest to emphasize side peaks

Experimental Results: 3) Longitudinal Phase space



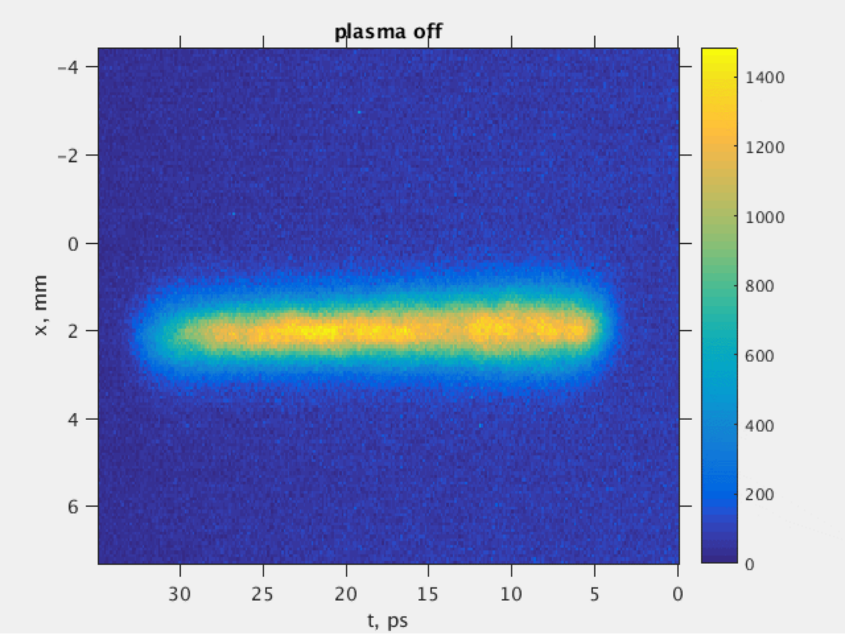


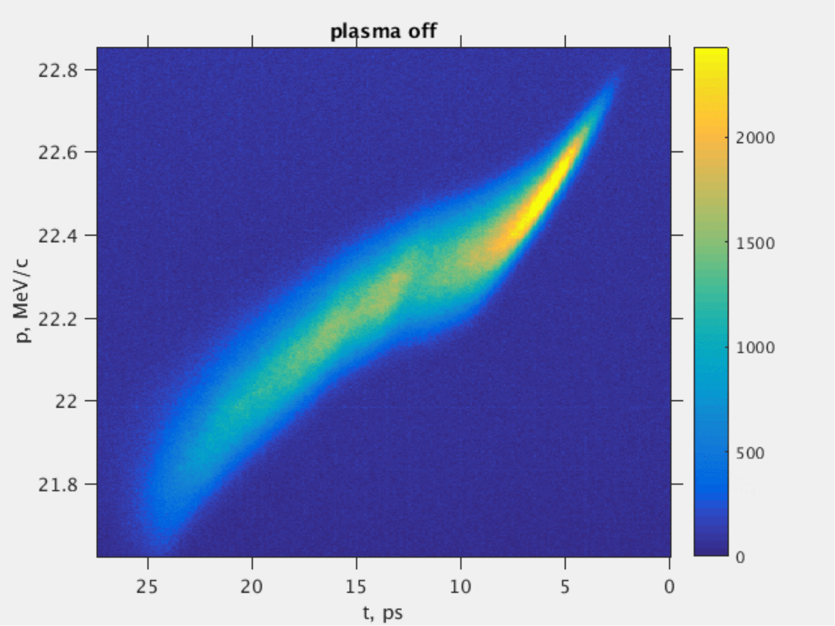


- Momentum modulation with 200 keV/c amplitude

Q=0.97 nC
Plasma density: $\approx 10^{14}$ cm^{-3}

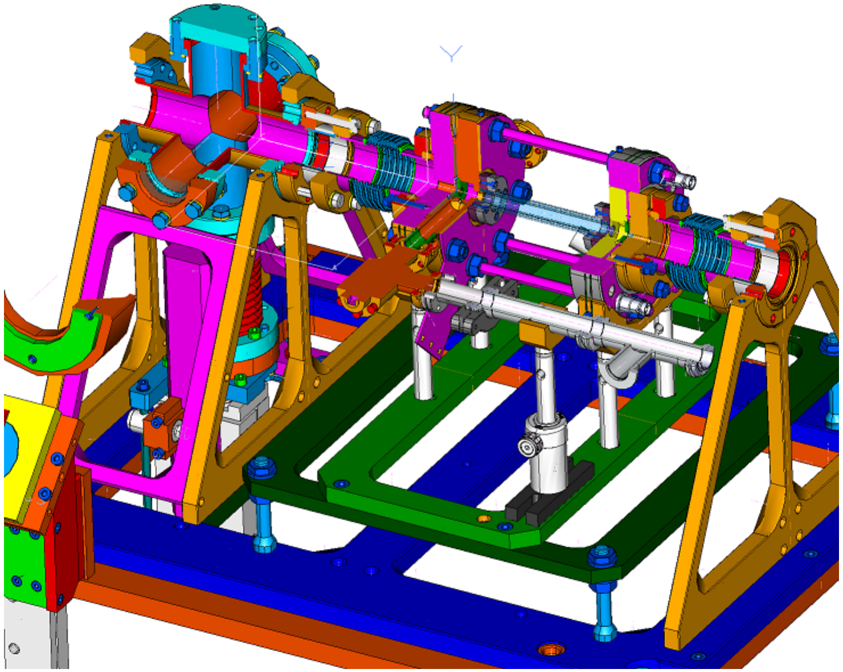
Experimental Results: Self-Modulation vs. Plasma Density

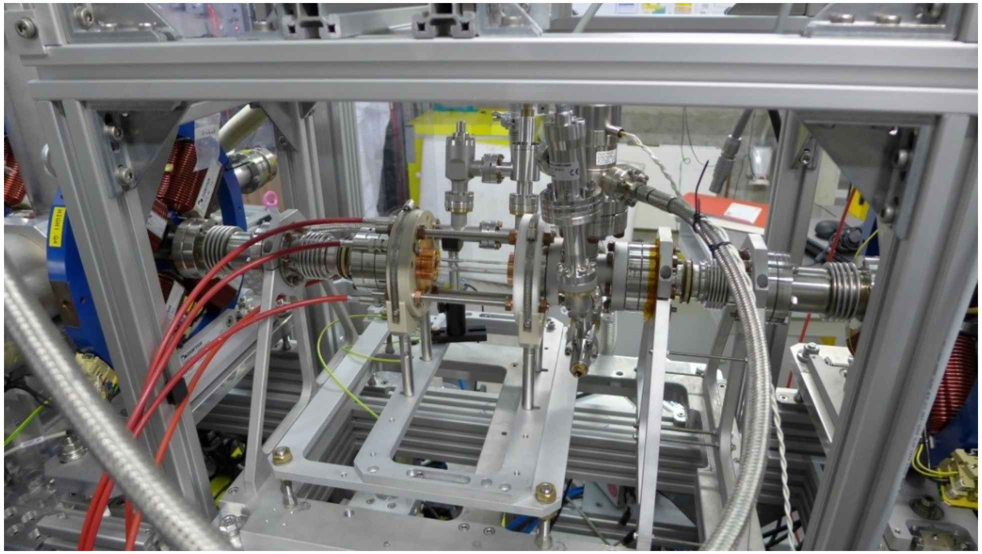




> Measured time resolved electron bunch for different delays of the electron bunch arrival time relative to the ionization laser pulse

Discharge Plasma Cell



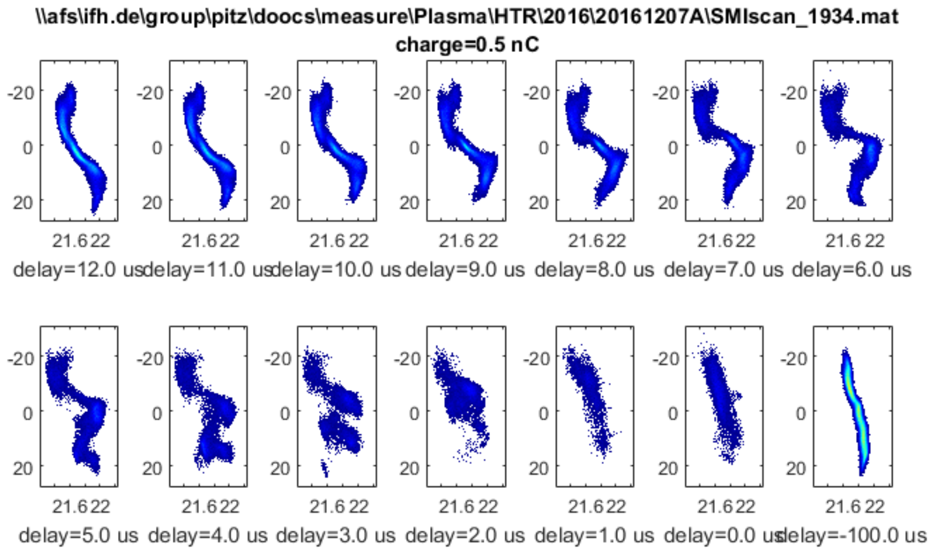


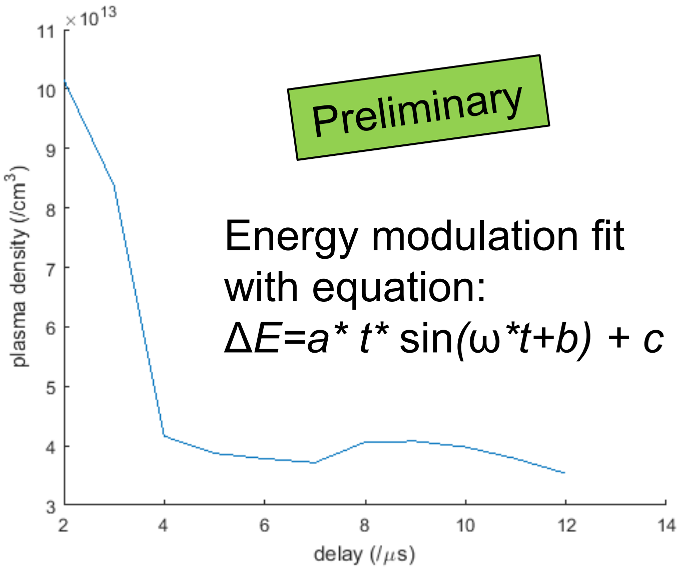
- Ar/H_2 gas at 0.1 – 10 mbar (sealed off)
- **10 cm plasma length**
- Max. voltage 2 kV, max. current 2 kA
- **Plasma densities up to several 10^{16} cm^{-3}** possible
- Pre-ionisation via glow discharge

SMI Experimental results with Discharge Plasma Cell

<u>Self-modulated bunch vs. discharge to electron beam delay</u>

- Vertical axis: time (streaked with TDS)
- Horizontal axis: momentum





Energy modulation fit with equation:
$\Delta E = a * t * \sin(\omega * t + b) + c$

> Self-modulation also seen with this plasma cell

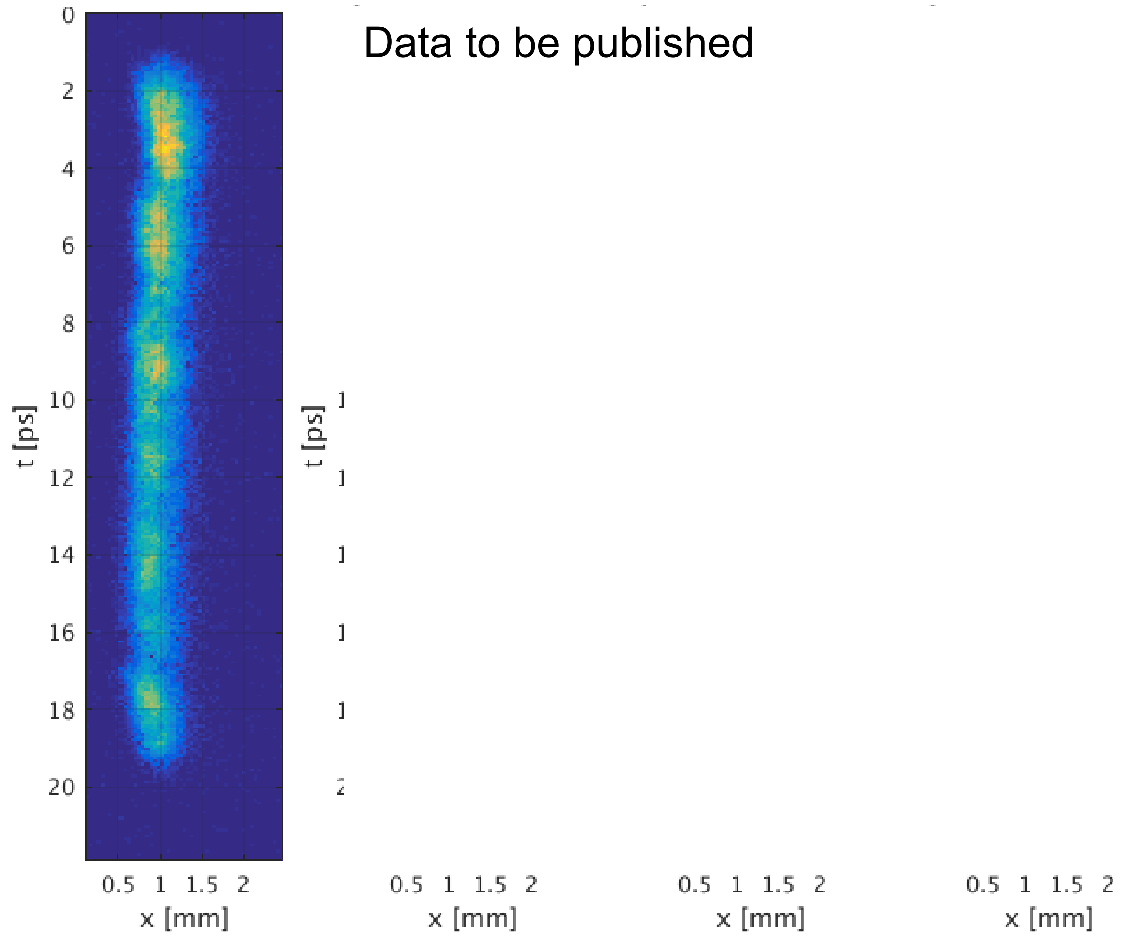
> Is utilized to measure plasma density (novel method)

Latest SMI Results with Discharge Plasma Cell

- Time resolved bunches at high plasma densities ($d \cdot 10^{15}$ cm^{-3})

Plasma off | d = 1.11 | d = 0.98 | d = 0.82

Data to be published



Latest SMI Results with Discharge Plasma Cell (LPS)

- For highest plasma density (2×10^{15} cm^{-3}) growth of modulation amplitude along the bunch (sign of SMI?)

Plasma off

2×10^{15} cm^{-3}

Data to be published

Growth to be cross-checked with simulations

21.8 22 22.2 22.4 22.6 22.8 23

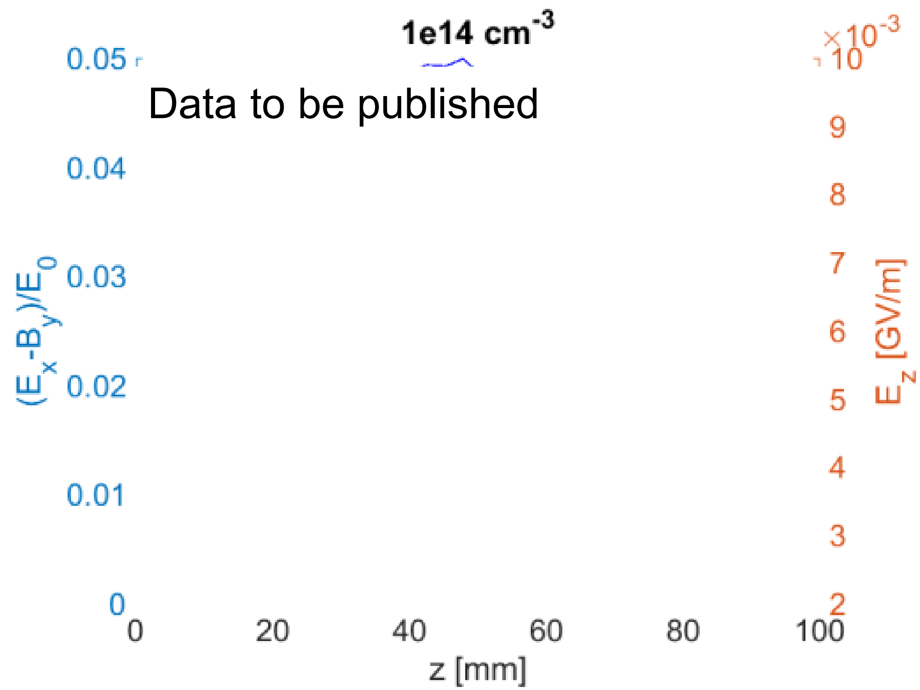
Momentum [MeV/c]

21.8 22 22.2 22.4 22.6 22.8 23

Momentum [MeV/c]

SMI Simulation Results

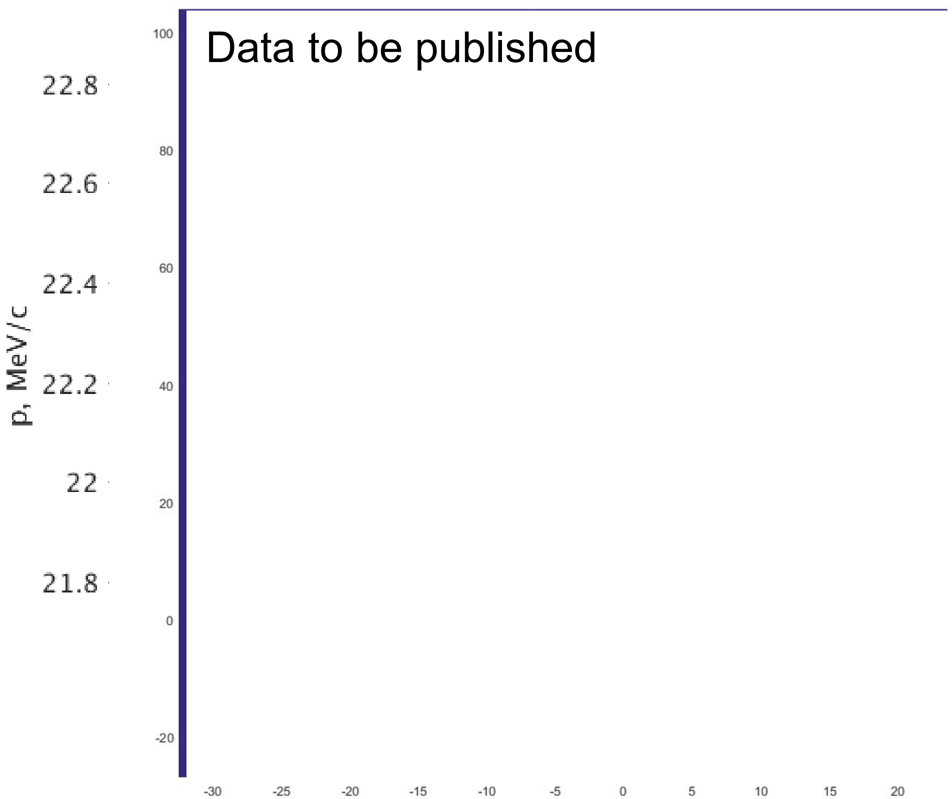
- Start-to-end of plasma cell simulation:
  - Beam transport to plasma cell with ASTRA
  - Beam-plasma interaction PIC simulation with HiPACE
  - Beam and plasma properties as in self-modulation experiment (Oct. 2016)
- Simulated transverse wakefield shows strong growth (starting point depends on beam focusing) and saturation
  - As expected if self-modulation instability is causing this behavior

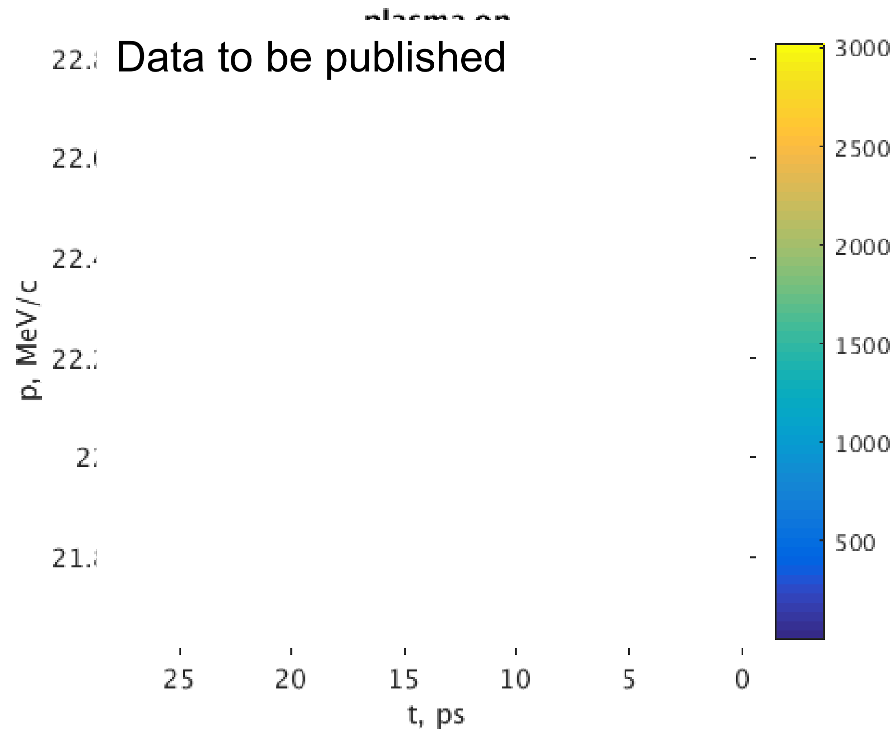


- Maximum transverse wakefields along the simulation box (solid lines)
- E_Z field of first maximum (dash-dotted lines)
- 3 focusing solenoid currents

SMI Simulation Results

- Comparison of measured and simulated longitudinal phase space
  - Good agreement





Summary

- Two plasma cells were built and put into operation at PITZ
  - Novel cross-shaped plasma cell with grooves (lithium heat pipe oven)
  - Discharge plasma cell
- Experimental results
  - Time resolved measurement: transverse oscillations
  - Energy spectrum: widening / side peaks
  - Longitudinal phase space: energy modulations
- Conclusions
  - Self-modulation was shown with strong indirect evidence that this is caused by the self-modulation instability
- Outlook
  - More experiments are planned, e.g. self-modulation amplitude vs. plasma channel length (movable beam block in ionization laser beam path) $\rightarrow$ direct demonstration of SMI