Overview of DESY and Accelerator R&D at the Photo Injector Test facility at DESY in Zeuthen (PITZ)

Matthias Gross for the PITZ Collaboration, Chiang Mai, Thailand, November 5th, 2018

Content:
• DESY: overview
• PITZ: introduction; projects
Deutsches Elektronen-Synchrotron
- National research centre of Germany
- Member of the Helmholtz Association
- Two sites: Hamburg and Zeuthen
- Hamburg since 1959, Zeuthen since 1992 DESY
- Together ≈2300 employees + more than 3000 guest scientists from over 40 countries each year

Research Topics
- Accelerators
- Photon Science
- Particle Physics / Astroparticle Physics
Research in Zeuthen

Astroparticle Physics
- Role of high-energy particles in the cosmic evolution
- Neutrino astronomy/cosmology, gamma astronomy, theoretical astroparticle physics, multimessenger astronomy

Particle Physics
- Search for the fundamental building blocks of nature and their interaction
- Experimental and theoretical particle physics

Accelerators
- Development of tomorrow’s accelerators
- Photoinjector Test Facility in Zeuthen (PITZ)
DESY in Zeuthen – Overview

Modern research centre
• More than 280 employees
• International participation in science and research
• Construction and development
• Mechanical and electronic workshops
• Computer centre
• Detector development
• Libraries, administration, communication
• School labs
Latest Science News from DESY in Zeuthen

12 July 2018: Breakthrough in the search for cosmic particle accelerators
• Scientists trace a single neutrino back to a galaxy billions of light years away

13 August 2018: World record – Low-draft electron bunches drive high plasma wakes
• Scientists achieve highest ratio of acceleration to deceleration in plasma wakes yet

10 October 2018: First CTA telescope inaugurated
• LST-1 makes its debut on the northern Cherenkov Telescope Array site
PITZ Collaboration Partners (formal contract signed)

Founding partners of PITZ:
- **DESY, HH & Z** (leading institute)
- **HZB (BESSY)** (A. Jankowiak): magnets, vacuum
- **MBI** (S. Eisebitt): cathode laser
- **TU Darmstadt** (TEMF, T. Weiland, H. DeGersem): simulations

Other national partners:
- **Hamburg university**:  
  - most PhD students;  
  - HGF-Vernetzungsfond;  
  - generation of short pulses  
  - plasma experiments
- **HZDR**:  
  - BMBF-PC-laser-project between MBI, DESY and HZDR, until ~2009;  
  - collaboration between HZB, HZDR, MBI and DESY in SC-gun-cluster

International partners:
- **IAP Nizhny Novgorod + JINR Dubna**: 3D elliptical laser pulses, THz radiation
- **INFN Frascati + Uni Roma II** (L. Palumbo, M. Ferrario): TDS and E-meter pre-studies
- **INFN Milano** (C. Pagani): photocathodes
- **INR Troitsk** (L. Kravchuk): CDS, TDS, Gun5
- **INRNE Sofia** (D. Tonev, G. Asova): EMSY + personnel
- **LAL Orsay** (A. Stocchi): HEDA1 + HEDA2
- **STFC Daresbury** (D. Angal-Kalinin, B. Militsyn): phase space tomography
- **Thailand Center of Excellence in Physics** (T. Vilaithong, Ch. Thongbai, S. Rimjaem): personnel
- **YERPHI** (V. Nikoghosyan) + **CANDLE** (V. Tsakanov, B. Grigoryan), **Yerevan**: personnel
Contact to Laser Experts at DESY

Help to set up short pulse laser program at CMU

- DESY Group is dedicated for laser developments around accelerators
- Group leader: Ingmar Hartl

- Small overview of lasers and activities within the FS-LA Laser Science and Technology Group
Photo Injector Test facility at DESY, Zeuthen site (PITZ)

Development, test and optimization of high brightness electron sources for SC linac driven FELs + applications:

- test-bed for FEL injectors, e.g. FLASH and European XFEL (gun cavities and photo injector subsystems → e.g. lasers)
- high brightness → small $\epsilon_r$ (projected and slice), lots of beam diagnostics
- further studies → e.g. cathodes: dark current, photoemission, QE, thermal emittance, … → applications like plasma acceleration, THz, UED, …

Pulse Train Time Structure:
PITZ and EXFEL run bunch trains with up to 600 (2700) laser pulses

RF gun
- L-band (1.3 GHz) 1.6-cell copper cavity
- $E_{\text{cath}} \gg 60\text{MV/m} \rightarrow 7\text{MeV/c e-beams}$
- 650us x 10Hz → up to 45 kW av. RF power
- $\text{Cs}_2\text{Te PC (QE=5-10\%)} \rightarrow$ up to 5nC/bunch
- LLRF control for amp & phase stability
- Solenoids for emittance compensation
Towards ultimate low emittance beams → 3D ellipsoidal pulses

- Laser shaping → key for optimizing photoinjector brightness.
- Ellipsoidal laser shaping benefits high bunch charge beams or CW guns (lower gun gradients).

Two methods to generate 3D ellipsoidal photo cathode laser pulses are under study:
Developing 3D ellipsoidal laser pulses

First experimental results – collaboration with IAP Nizhny Novgorod

- **Proof of principle demonstrated with IAP system (single SLM → dual path) at PITZ in 2016**

  Comparison with simulated e− beam shapes (500pC): similarity in shape

  ![Comparison with simulated beam shapes](image)


- **Redesign to true double SLM setup**
  - Improved stability: commercial Pharos laser oscillator
  - Improved shaping capabilities: independent masking in x-y, spectrograph feedback
  - Next: - experiments to quantify shape preserving FHG conversion with angular chirp
    - true 3D shaping with Volume Bragg Gratings

  C. Koschitzki et al., Proc. 9th IPAC, WEPMF059 (2018)
Development of green cathodes on INFN LASA plug design

Collaboration with INFN LASA Milano

- Test reliable “green” cathodes (K-Cs-Sb compound) in PITZ RF-Gun (high cathode gradient + fairly high duty cycle)
  - First sequential deposition on test sample in week 47/2017 (“proof of principle”)
- Long term measurement
  - Total extracted charge over more than 3 months
    - >1000C
  - QE versus time:
    - QE decrease depends on light power density (fatigue effect?)
- Next: Design new source layout in view of co-evaporation in the near future
  - Increase QE
  - Increase life time

**QE versus time**

- **broad band LED** power density (~$18\,\text{mW/cm}^2$)
- **Laser Driven Light Source** power density (~$21\,\text{mW/cm}^2$)

**Total Extracted Charge**

- No light

**K$_2$CsSb spectral responses**

- QE = 4.6 % @ 514 nm
Progress in modelling the photoemission process

Collaboration with TU Darmstadt and colleagues at DESY in HH

- Photoemission beyond linear region is not well simulated.
- Short Gaussian laser case is improved using Core + Halo model.
- For long laser pulses more relevant to FELs (e.g. Flattop), agreement is worse → work needed.

→ Ye Chen et al., NIM A 889 (2018) 129-137.

Collaborations with TU Darmstadt
  - 3D photoemission modeling
  - Cathode physics model

Best beam emittance located in transition region, needs more accurate photoemission modeling.
Next generation of pulsed RF gun under production

Fabrication of Gun 5 for higher stability & reliability has started (Collaboration with INR Troitzk)

- New features of Gun 5 (see V. Paramonov et al., NIM A 854 (2017) 113-126.):
  - includes **RF probe** → + fine control of RF stability
    + allows symmetric power coupler (2 input arms → reduced load on RF windows)
    - possible sensitivity on pulsed heating → **experimental tests needed**
  - increased **water cooling** and reduced **deformation** over RF pulse → more reliable operation at high duty cycle
  - improved cell **geometry** + elliptical irises → reduced RF heating & surface field strength

→ First (central) part under production now
CW gun related R&D proposal at PITZ

CW electron source for CW upgrade of FLASH & XFEL

- Primary: Superconducting L-band CW gun (DESY, HZB, HZDR)
  - Green cathode testing at PITZ
  - Beam dynamics testing at PITZ for CW gun gradient; …
- Backup: Normal conducting CW gun (LBNL)
  - At PITZ, a scaled & improved NC CW gun design is under planning for XFEL

PITZ gun
1.3 GHz, ~40 kW, ~0.65% duty cycle
6.5 MeV/c, ~40 MV/m @ photoemission

CW NC gun @ LBNL
1.3/n GHz, 100~200 kW
1~2 MeV/c, 20~30 MV/m @ photoemission

Depending on the funding availability (~2.5 M€ hardware investment) and based on LBNL experience, it takes >5 to 12 years from gun design to beam demonstration.

Current development plan at PITZ
Phase-I, CW gun design & fabrication (2017~2020)
Phase-II, CW gun RF & cathode demonstration (2021~2022)
Phase-III, Integration into PITZ beamline for beam brightness measurement (2023~2025)
Beam driven PWFA Research at PITZ

A flexible platform for exploring beam-plasma interactions

- **Flexible temporal bunch forms** (advanced photocathode laser pulse shaping capabilities)
- Developed and **benchmark beam diagnostics** in place (RF deflector, dipole spectrometer, …)

Novel cross-shaped lithium heat pipe oven

- **Ionization laser is coupled in through side windows** → flexibility in plasma channel length and density profile

Discharge plasma cell (argon)

- **Simple setup**
- **Scalable in plasma density**

O. Lishilin et al., Proc. of IPAC2017, TUPIK017

G. Loisch et al., “Jitter mitigation in low density plasma sources for wakefield accelerators”, NIM A, to be published
• Use high energy proton beams from SPS to drive plasma wave
• Convert proton beam energy to accelerate electron beam in single stage

![Diagram of AWAKE Facility at CERN](https://example.com/diagram)

Courtesy: Edda Gschwendtner

High accelerating gradient requires short bunches ($\sigma_z$ less than 100µm)

Existing proton machines produce long bunches (10cm)

Acceleration field (Caldwell et al., Nature Physics, 2009):

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

Self-modulation!
PWFA Highlight: Self-Modulation of a Long Electron Bunch

RF deflector reveals first unambiguous experimental signature

- Demonstration at PITZ: characterization of self-modulation with electron beam

**Time resolved bunch** (d × n_p = 10^{15} cm^{-3})

<table>
<thead>
<tr>
<th>Plasma off</th>
<th>d = 1.11</th>
<th>d = 0.98</th>
<th>d = 0.82</th>
</tr>
</thead>
</table>

**Longitudinal phase space** (n_p = 10^{14} cm^{-3})

Successful experiments → M. Gross et al., PRL 120, 144802 (2018)

Additional studies planed for 2019
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

Time resolved bunch

Longitudinal phase space
PWFA Highlights: High Transformer Ratio in Plasma

First detection of increased transformer ratio with shaped driver in plasma

- **Beam loading theorem:** transformer ratio $TR \leq 2$ for symmetric drive bunch; $TR = \frac{E_{acc}}{E_{dec}}$

- **Idea:** Increase ratio of witness energy gain to driver energy loss with asymmetric drivers

- **Demonstration at PITZ:** Time resolved energy measurement (slice energy) by using ~double triangular drive bunch

- **Experimental result:** $TR = 4.6 \pm 2.2$


\[ \rightarrow \] G. Loisch et al., "Photocathode laser based bunch shaping for high transformer ratio plasma wakefield acceleration", NIM A, published online
Bunch Microstructure Generation with DLWs at PITZ

**PIs:** F. Lemery (CFEL, DESY) and P. Piot (APC FNAL)

- **Using Dielectric Lined Waveguides - DLW**

  - **Conductive jacket**
  - **Dielectric lining (ε_r)**
  - **Vacuum core**
  - **Inner radius (a)**
  - **Outer radius (b)**

  \[(a, b, \epsilon_r, L) = (450 \, \mu m, 550 \, \mu m, 4.41, 5 \, cm)\]

  **Parameter** | **Symbol** | **Nominal** | **Unit**
  --------------|------------|------------|----------
  Laser launch phase | \(\phi_l\) | 0 | deg |
  Laser diameter | \(d\) | 2 | mm |
  RF gun peak field | \(E_0\) | 60 | MV/m |
  Max. p_x at DLW | \(p_x\) | 1.03 | MeV/c |
  Linac phase | \(\phi\) | 0 | deg |
  Linac power | \(P\) | 2.8 | MW |
  Linac peak field | \(E_1\) | 18 | MV/m |
  Bunch charge | \(Q\) | 1.1 | nC |
  Final beam momentum | \(p_0\) | 20-24 | MeV/c |

**E-beam current profile**

- **without (blue trace)**
- **with DLW (red trace)**

  \(\lambda = 1.03 \, mm\); The peaks are consistent with the wavelength of the structure 3.3 ps.

**Measured Longitudinal Phase Space**

- **DLW out**
- **DLW in**

*F. Lemery et al., Experimental demonstration of ballistic bunching with dielectric-lined waveguides at PITZ, IPAC 2017, WEPAB122*

⇒ F. Lemery, P. Piot, et al., paper submitted to PRL
IR/THz SASE source for pump-probe experiments @E-XFEL

PITZ-like accelerator can enable high power, tunable, synchronized IR/THz radiation

- Accelerator based IR/THz source meets requirements for pump-probe experiments (e.g. the same pulse train structure !)
- Construction of radiation shielded area for installing reduced copy of PITZ is possible close to user experiments at E-XFEL
- Prototype of accelerator already exists → PITZ facility at DESY in Zeuthen
- Required beam (~4nC, \( I_{\text{peak}} \sim 200\text{A} \)) and generation of THz radiation already demonstrated at PITZ
- → PITZ can be used for proof of principle and optimization!

Possible with PITZ (simulation)

PITZ beam application: femtosecond $e^-$ diffraction

Femtosecond & femtocoulomb $e^-$ beam generation at PITZ

- 'REGAE mode' (sub 10 fs)
- Velocity debunching
- L-band booster
- Velocity compression

Preliminary simulations

<table>
<thead>
<tr>
<th>Gun &amp; booster RF amplitude &amp; phase stability</th>
<th>e beam TOF jitter (fs, rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>3e-4, 0.06 deg</td>
<td>200</td>
</tr>
<tr>
<td>1e-4, 0.01 deg</td>
<td>50</td>
</tr>
</tbody>
</table>

~6000 pulses/s available at PITZ

→ low density / thin film samples

complementary to & combinable with XFEL
First static electron diffraction test at PITZ

Collaboration between PITZ, Max-Born-Institute (MBI) and Fritz-Haber-Institute (FHI)

- DESY/PITZ: Installation, beam experiment, …
- MBI: Sample substrate, Au sample, EMCCD, beam experiment, …
- FHI: WS$_2$ sample, diffraction pattern analysis, …

PITZ Gun

Sample

Detector

Au (polycrystal, 100 nm thick)

WS$_2$ (single crystal, 50-60 nm thick)

~320 fC, ~100 nm.rad
First static electron diffraction test at PITZ

- 1st test results

<table>
<thead>
<tr>
<th>Electron beam at sample</th>
<th>1st Test</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>~4</td>
<td>MeV</td>
</tr>
<tr>
<td>Wavelength</td>
<td>~0.3</td>
<td>pm</td>
</tr>
<tr>
<td>Pulse rate</td>
<td>10 ~ 100</td>
<td>pulse/s</td>
</tr>
<tr>
<td>Electron per pulse</td>
<td>~2x10^6</td>
<td>e/pulse</td>
</tr>
<tr>
<td>Bunch FWHM length</td>
<td>~2</td>
<td>ps</td>
</tr>
<tr>
<td>Normalized emittance</td>
<td>~100</td>
<td>nm.rad</td>
</tr>
<tr>
<td>Beam rms size</td>
<td>~250</td>
<td>um</td>
</tr>
<tr>
<td>Transverse coherence length</td>
<td>~1.9</td>
<td>nm</td>
</tr>
</tbody>
</table>

- Some conclusions:
  - PITZ beam demonstrated good diffraction quality on solid state samples with ~ps time resolution and ~nm transverse coherence length.
  - PITZ bunch train made signal accumulation time short for diffraction pattern with very good signal to noise ratio.
  - With gun, booster and laser phase jitter improvements → sub-ps to 100 fs time resolution is expected.
  - Further tests on using high quality PITZ bunch train for UED are under planning.
Summary

- **PITZ:** well developed **photo injector test facility**
  - detailed beam **diagnostics** available
  - broad scientific program

- One of leading institutes on optimizing **beam quality**
  - next step: generate high charge **quasi 3D ellipsoidal electron beams** for ultimate beam quality

- Developments towards “**green**” **photocathodes** have started at INFN LASA Milano

- Work on photoemission modeling ongoing

- **Next generation** of **pulsed gun** under production, first thoughts on **NC CW guns**

- Very successful experiments performed on **beam driven plasma acceleration**:
  - **self-modulation** of long particle bunches
  - **high transformer ratio** in plasma with shaped particle beam

- Successful generation of **bunch microstructure** using dielectric lined waveguides

- Promising feasibility studies for **high power, tunable THz source** for P&P experiments at European XFEL

- First successful **static electron diffraction** experiments using bunch trains

- Purpose of visit: using collaboration contacts to set up short pulse laser program at CMU