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

Frank Stephan for the PITZ Collaboration, Breckenridge, August 12th-17th, 2018

Content:
- PITZ: collaboration, facility, operation parameters
- Towards ultimate low emittance beams
- Development of “green” photo cathodes
- Next generation of pulsed RF gun
- First considerations towards upgraded NC CW gun design
- Applications:
  - **Beam driven plasma acceleration:**
    - Self modulation of long particle beams
    - High transformer ratios in plasma
  - Bunch microstructure generation with dielectric lined waveguides
  - High power, tunable THz source for pump-probe experiments at E-XFEL
  - First static UED measurements
- Summary & Outlook
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): personnel
  - YERPHI (V. Nikoghosyan) + CANDLE (V. Tsakanov, B. Grigoryan), Yerevan: personnel

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**contract on green photocathodes**
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 $\varepsilon_{tr}$ (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
- $E_{cathe} > \sim 60 \text{MV/m} \rightarrow 7 \text{MeV/c e-beams}$
- 650us x 10Hz → up to 45 kW av. RF power
- $\text{Cs}_2\text{Te PC (QE=5-10\%)} \rightarrow \text{up to 5nC/bunch}$
- LLRF control for amp & phase stability
- Solenoids for emittance compensation

<7 MeV <25 MeV
Towards ultimate low emittance beams \rightarrow 3D ellipsoidal pulses

- Laser shaping \rightarrow 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:

![Graph showing beam emittance vs. bunch charge](image)

Still WR on lowest measured projected emittances

M. Krasilnikov et al., PRST-AB 15, 100701 (2012)

Spatial Light Modulator (SLM) shaper

NEW: 3D Volume chirp Bragg grating

Collaboration with IAP, JINR

IR cross correlation measurements

rotational symmetric
Developing 3D ellipsoidal laser pulses

First experimental results

- 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

- Redesign to true double SLM setup based on commercial Pharos laser
  
  - Improved stability: Polaris mounting system, new amplifier scheme with commercial Pharos: 200 µJ, 0.1 MHz with 245 fs pulse duration @ 1030 nm
  
  - 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

The INFN LASA Milano plug design is in operation at PITZ / XFEL / FLASH / REGAE / SINBAD / LBNL / FNAL.

- The aim of this activity is to grow reliable “green” cathodes (K-Cs-Sb compound) on the INFN plugs and test them in the PITZ RF-Gun (high cathode gradient + fairly high duty cycle)
  - First **sequential deposition** on test sample in week 47/2017 (“proof of principle”)
    - Sb 10 nm
    - K until max QE
    - Cs until max QE
    - Repeated on 1 Dec 2017
  - **Long term measurement**
    - Total extracted charge over more than **3 months**
    - QE versus time
      - Based system pressure in the low 10^{-10} mbar
      - QE decrease depends on light power density (fatigue effect?)
        \[ \text{QE} \approx 4.6\% \text{ @ 514 nm} \]
      - still reasonable QE
    - Next: Design new source layout in view of co-evaporation in the near future
Next generation of pulsed RF gun under production

Fabrication of Gun 5 for higher stability & reliability has started

- 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

Cavity
RF pickup

→ First (central) part under production now
First considerations towards upgraded NC CW gun design

Backup design for European XFEL CW upgrade

- CW gun design collaboration
  - DESY group visit to LBNL and SLAC (2/2018).
  - Collaboration with LBNL on NC CW gun development.

- PITZ design progress (still preliminary !!!)
  - Design tool benchmarked using APEX gun model (187 MHz).
  - RF design of a 217 MHz gun for European XFEL started this year, targeting ~30 MV/m at cathode, ~100 kW RF power.
  - Current gun design plugged into LCLS-II injector model shows emittance (0.10~0.16 μm) and high order energy spread (3~4 keV rms) @ 100 pC with I_{peak}=10A.
  - Gun geometry, injector layout and optics are still under further optimizations.

Preliminary design of DESY VHF gun (217 MHz)

Preliminary injector simulation with DESY VHF gun (100 pC)
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**edi**ned 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**

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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
PWFA Highlights: Self-Modulation of a Long Electron Bunch

RF deflector reveals first unambiguous experimental signature

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

- Motivation: AWAKE experiment at CERN \(\rightarrow\) convert SPS proton beam energy into electron acceleration in a single stage

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

  \[ E_{z,max} = 240(MV \, m^{-1}) \left( \frac{N}{4 \times 10^{10}} \right) \left( \frac{0.6}{\sigma_z [\mu m]} \right)^2 \]

  now \(\sigma_z(10\text{cm}); \text{aim } \sigma_z(100\mu\text{m})\)

- \(\sigma_z\) needs to be reduced significantly \(\rightarrow\) **Self-modulation**

- **Successful experiments** \(\rightarrow\) M. Gross et al., PRL 120, 144802 (2018)

Additional studies planned for 2018
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; $TR = \frac{E_{\text{acc}}}{E_{\text{dec}}}$

- **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:** $TR = 4.6^{+2.2}_{-0.7}$

Bunch Microstructure Generation with DLWs at PITZ

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

- Using Dielectric Lined Waveguides - DLW

Parameter | Symbol | Nominal | Range | Unit
---|---|---|---|---
laser launch phase | $\phi_1$ | 0 | - | deg
laser spot radius | $r_0$ | 2 | - | mm
laser pulse duration | $L_p$ | 13 | [10, 20] | ps
RF gun peak field | $E_0$ | 60 | [45, 60] | MV/m
line phase | $\phi_L$ | 0 | [-30, +10] | deg
line voltage | $V_L$ | 14 | [10, 18] | MV
bunch charge | $Q$ | 1.1 | [0.020, 0.2] | nC
beam momentum | $p_0$ | 21.8 | [16, 22] | MeV/c

**DLW permittivity**: $\varepsilon_r = 4.11$
**DLW1 inner radius**: $r_1 = 400 \pm 50$ μm
**DLW1 outer radius**: $r_2 = 500 \pm 50$ μm
**DLW1 length**: $l_1 = 50.0 \pm 0.1$ mm
**DLW2 inner radius**: $r_3 = 700 \pm 50$ μm
**DLW2 outer radius**: $r_4 = 900 \pm 50$ μm
**DLW2 length**: $l_2 = 80.0 \pm 0.1$ mm

- Measured Longitudinal Phase Spaces


E-beam current profiles

> Different booster phases
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

Simulation of THz SASE FEL @PITZ

Required beam (~4nC, I_{peak}~200A) already demonstrated at PITZ

⇒ PITZ can be used for proof of principle and optimization!
Planned installation of LCLS-I undulators in PITZ tunnel annex

Will be used for proof-of-principle experiments at PITZ

Currently improving radiation shielding and preparing for operation permission for tunnel annex
First static electron diffraction tests at PITZ
Collaboration between PITZ, Max-Born-Institute (MBI) and Fritz-Haber-Institute (FHI)

- PITZ bunch train (up to $\sim 10^4$ pulses/sec) reduces signal accumulation time for
diffraction patterns for better signal to noise ratio.

**Summary of 1st test**

<table>
<thead>
<tr>
<th>e$^-$ beam at sample</th>
<th>1st Test</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>$\sim4$</td>
<td>MeV</td>
</tr>
<tr>
<td>Electron per pulse</td>
<td>$\sim2\times10^6$</td>
<td>e$/pulse$</td>
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<tr>
<td>Bunch FWHM length</td>
<td>$\sim2^*$</td>
<td>ps</td>
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<tr>
<td>Normalized emittance</td>
<td>$\sim100$</td>
<td>nm.rad</td>
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<tr>
<td>RMS beam size at sample</td>
<td>$\sim200$</td>
<td>µm</td>
</tr>
<tr>
<td>Transverse coherence length</td>
<td>$\sim1.9^{**}$</td>
<td>nm</td>
</tr>
</tbody>
</table>

*Buncher off.  **No beam aperture yet.
Summary

- **PITZ**: well developed **photo injector test facility**
  - detailed beam **diagnostics** available
  - broad scientific program
  - open for new collaborations → contact me!

- 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 (and hybrid) 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

- (Simulation studies ongoing to use PITZ for Laboratory Astrophysics experiments)