The Photo Injector

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Outline

• TTF photo injector parameters and layout
• Optimization of the photo injector at PITZ
  – RF gun conditioning, high power test
  – Cathode laser pulse shapes
  – Emittance optimization
• Current status of the TTF injector
• Further developments on the photo injector
• Summary
TTF2 Photo Injector Parameters

Brightness of the electron beam is crucial for SASE FEL’s → LINAC, photo injector

\[ B_n = \frac{2I}{\varepsilon_n^2} \]

Design electron beam parameters:

- Charge 1 nC / bunch
- Normalized emittance from injector 1.2 mm mrad
- Energy spread 0.1 %
- After 2 compression stages: bunch length 50 µm, peak current 2.5 kA
TTF2 Photo Injector Layout (design)

- RF gun
  - 4 - 5 MeV

- Superconducting TESLA module (ACC1)
  - 100 - 150 MeV

- 3rd harmonic cavity ACC39
  - 130 - 150 MeV

- Laser
  - Longitudinal Phase Space correction applying 3rd harmonic (3.9GHz) cavity

- Longitudinal Phase Space
  - Reduce space charge effect on the cathode
  - Flat-top longitudinal laser profile
  - 20ps
TTF2 Photo Injector Layout (design)

Space charge compensating scheme by applying solenoid field

Emittance conservation using booster with proper position and gradient - matching conditions:

\[ \gamma' = \frac{2}{\sigma_w} \sqrt{\frac{I}{3I_0\gamma}} \]
TTF Photo Injector Optimization at PITZ

Photo-Injector Test Facility at DESY Zeuthen (PITZ)
Photo-Injector Test Facility at Zeuthen (PITZ)

Collaboration:

BESSY Berlin, CCLRC Daresbury,
DESY, INFN Frascati,
INFN Milano, INR Troitsk,
INRNE Sofia, LAL Orsay,
MBI Berlin, TU Darmstadt,
U Hamburg, YERPHI Yerevan
Goals of PITZ

- test facility for FELs: VUV-FEL, XFEL
  - small transverse emittance (1 mm mrad @ 1 nC)
  - stable production of short bunches with small energy spread
  - further studies: dark current, QE, BBA, thermal emittance, …
  - detailed comparison with simulations
- extensive R&D on photo injectors in parallel to TTF operation
- test and optimize rf guns for subsequent operation at the VUV-FEL and XFEL
- test new developments (laser, cathodes, beam diagnostics)
RF Gun Conditioning: Long Pulses, High Power

RF Power source: 5 MW Klystron
RF Gun cavity: 1.5-cell copper cavity operated at 1.3 GHz, coaxial coupler

- rf pulse length: 900 µs
- repetition rate: 10 Hz
- gradient: ~42 MV/m at the cathode (~3 MW)

⇒ duty cycle: 0.9 %, average rf power: 27 kW

fulfills VUV-FEL RF parameter requirements

goals for XFEL → 60 MV/m, ≤ 650 µs, 10 Hz
Cathode Laser System

PITZ → test facility for the cathode laser

Max-Born-Institute, Berlin

*diode-pumped* Nd:YLF preamplifier

*diode-pumped* Nd:YLF oscillator

Pulse shaper

*diode-pumped* Nd:YLF booster amplifier

2-stage diode-pumped Nd:YLF amplifier

2-stage flashlamp-pumped Nd:YLF amplifier

Faraday isolator

Pulse picker 1 MHz

pump diodes

pump diodes

fast current control

fast current control

AOM EOM AOM

*f\text{round trip} = 27\text{ MHz}*

E_{\text{micro}} = 16\text{ }\mu\text{J}

P_{\text{burst}} = 16\text{ W}

E_{\text{micro}} = 200\text{ }\mu\text{J}

P_{\text{burst}} = 200\text{ W}

E_{\text{micro}} = 30\text{ }\mu\text{J}

E_{\text{burst}} = 24\text{ mJ}

UV (262 nm)

to photocathode

flat-top pulses

Pulse train from the oscillator

Amplified output train

Shot-to-shot optimizer

800\mu s

Emicro = 16 \mu J
Pburst = 16 W
Emicro = 200 \mu J
Pburst = 200 W
Emicro = 30 \mu J
Eburst = 24 mJ
UV (262 nm)

*more details → talk by S. Schreiber*
Until 23.06.2003 - Gaussian longitudinal laser shape:

FWHM = 7 ± 1 ps

Minimum measured emittance

≥ 3 mm mrad

On 23.06.2003 longitudinal shape changed to flat top

FWHM ≈ 18-23 ps

rise and fall time about 5-8 ps

1.6 mm mrad
The size of the beamlet is measured for three slit positions: 

\[ y_n = \langle Y \rangle_{\text{screen}^2} + n \cdot 0.7 \sigma_y \text{screen}^2 \]

\[ n \in \{-1, 0, 1\} \]
PITZ: Transverse Beam Size and Emittance

Emittance Optimization at PITZ

- Longitudinal laser profile
- Laser spot size on the cathode
- Emittance scan (RF Phase, Imain)
- Bucking solenoid tuning (Ibuck)
Simulated Transverse Emittance

ASTRA Simulation:
Normalized emittance as a function of rf gun phase and main solenoid peak field

Parameters used for the simulation:
- charge = 1 nC
- longitudinal laser profile:
  - flat top
  - 20 ps FWHM
  - 5 ps rise/fall time
- transverse laser profile
  - homogeneous
  - $\sigma_{x,y} = 0.6$ mm
- max. gradient at the cathode: 42 MV/m
Transverse Emittance Measurements

Running conditions:
~ 42 MV/m at the cathode
1 nC charge (re-adjusted for each RF phase)

Transverse laser profile
\[ \sigma_x = 0.51 \pm 0.02 \text{ mm} \]
\[ \sigma_y = 0.62 \pm 0.02 \text{ mm} \]

Temporal laser profile
FWHM \approx 20 \text{ ps}, \text{ rise/fall} \approx 5 \text{ ps}

Measured Normalized Emittance as a Function of RF Phase and Main Solenoid Current

Horizontal

Vertical
PITZ: Fine Tuning With Bucking Solenoid

- good agreement with beam dynamics simulations
- rf gun installed at the TTF in January 2004

Optimum settings
Q = 1 nC,
Φ = Φ₀ – 5°
I_{main} = 305 A
I_{buck} = 20-25 A

1.3 GHz 1 1/2 cell RF Gun

bucking solenoid
main solenoid

- good agreement with beam dynamics simulations
- rf gun installed at the TTF in January 2004
Improvement at PITZ in 2004

Gun cavity Prototype #1 – test for higher RF gradients (~45MV/m @cathode)

- min. emittance improved 1.5 → 1.3 mm mrad
- geom. average improved 1.7 → 1.6 mm mrad

\[ Q = 1 \, \text{nC}, \]
\[ \Phi = \Phi_0 \]
\[ I_{\text{buck}} = I_{\text{main}} \times 0.075 \]

Flat-top transverse laser profile:
\[ \sigma_x = 0.57 \pm 0.02 \, \text{mm} \]
\[ \sigma_y = 0.58 \pm 0.02 \, \text{mm} \]

Preliminary results 24.8.2004
In January 2004 PITZ Gun was installed at TTF
Laser driven RF gun has been smoothly commissioned

A complete TESLA module with eight 9-cell Nb accelerating cavities to boost the beam energy to 130 MeV
- The first 4 → moderate gradient (12 MV/m)
- The last 4 → higher gradient (20 MV/m)
- During commissioning all cavities have been operated with 12 MV/m (beam energy 100 MeV)

Injector commissioned in February – June 2004
Emittance Measurements (TTF)

- Four monitor method using OTR
- Beam size measured at four screens in a FODO lattice of six quadrupoles (fixed quad current)
- Emittance and Twiss parameters calculated from the measured beam sizes and beam size errors using chi-square fitting
- Bunch compressor is bypassed

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<th>PITZ</th>
<th>TTF</th>
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<td>Beam energy</td>
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<td>Optimum solenoid</td>
<td>~ 305A</td>
<td>~ 280A</td>
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Pulse shaper not yet installed: longitudinal shape Gaussian
Pulse length measured with a streak camera
\[ \sigma = 4.4 \pm 0.1 \, \text{ps (UV)} \]

Longitudinal laser profile

more details → talk by H. Schlarb
Further Developments at PITZ for VUV-FEL and XFEL

PITZ2: Large extension of the facility and its research program
Outlook PITZ 2

Towards to the XFEL Photo Injector:

- 60 MV/m at the cathode
- Cathode laser improvement
- Thermal emittance study
- Wakefield effect study (vacuum mirror, etc)

• 60 MV/m at the cathode
• Cathode laser improvement
• Thermal emittance study
• Wakefield effect study (vacuum mirror, etc)
Summary

• VUV FEL photo injector capable of producing high brightness electron beams

• RF gun has been optimized and characterized at PITZ → smooth commissioning at TTF

• Minimum transverse normalized beam emittance $\sqrt{\varepsilon_x \varepsilon_y}$:

  • 1.7 mm mrad measured at PITZ  
    (Flat-top laser profile / $E_{\text{beam}}$=4.2MeV / slit-scan method)

  • ~3 mm mrad measured at TTF  
    (Gaussian laser profile / $E_{\text{beam}}$=100MeV / four monitor method)

• Further improvements of the photo injector are ongoing