TESLA Test Facility

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XFEL Electron and Photon Diagnostics

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Outline

• Requirements
• Examples
  - VUV FEL/TTF2
  - European XFEL
• Hotspots
• System Overview
  - Electron Beam Diagnostics
  - Photon Beam Diagnostics

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Requirements

• SASE is a statistical process
  - Photon Beam Parameters change from Pulse to Pulse
  - Diagnostics has to provide Data on Shot to Shot Basis
• SASE is based on Exponential Amplification
  - Beam Quality has to be controlled/preserved with tight Tolerances
  - Need an integrated View and Treatment of Photon and Electron Data
• Users and Machine Operators need all Data
  - Pulse by Pulse and Bunch by Bunch

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LINAC - Storage Rings

LINAC
• Pulsed Systems
  - high Fluctuations
• Triggered Electronics have to take Pulses with the rep. Rate of the Bunches.
  (5 MHz @ XFEL)

Storage Rings
• Closed loop Equilibrium System
• Watch beam Parameters under steady state Conditions.
• Systems can be much slower and average over long Times.
• Precise Measurements in the Frequency Domain.

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... further Complication

What do Monitors see:
  - Mean value of charge per bunch
  - Mean value of position per bunch
  - Projected emittance
  - ...

Slice Parameters are essential for the FEL process!

Longitudinal Charge Distribution at TTF (“Femtosecond Mode”)

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Time Structure of Superconducting Linacs

• Repetition rate
  - 100ms
  - Duty cycle ~ 0.8% (XFEL 0.65%)

• Macro-pulse
  - 1-9 mA
  - 800 μs (XFEL 650 μs)
  - Ipeak ~ 2.5 kA

• Bunch
  - 1 nC
  - 100 fs
  - 2-5 kA ~ ps

• Slice
  - 10 fs

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Distribution of Diagnostics

- **LINAC**
  - Gun determines Beam Quality, later it gets only worse
  - Beam Quality is vulnerable by Space Charge at low Energy
  - Beam gets more stiff (-> predictable) during acceleration
  - BC’s introduce Emittance Heating and Instabilities
- **High Quality Diagnostics required at the Beginning**
  - Make sure, that the Beam has required Quality
  - Match the beam between:
    - Injector (space charge dominated)
    - and the LINAC (linear optics)
- **Longitudinal Diagnostics difficult at High Energies**
  - Check longitudinal properties directly after the space charge dominated part

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Example: VUV FEL/ TTF2

- **Injektor II**
  - Gun: 2 BPMs, 1 Toroid, 3 Screens, 3 F-Cups, 4 Losses
  - BC2: 9 BPMs, 2 Toroids, 6 Screens, 4 Wirescanners, 1 Phase, 1 Widerstand, FIR Diagnostics, 6 Losses
  - BC3: 6 BPMs, 2 Toroids, 4 Screens, 1 Wirescanner, 1 Phase, 1 Widerstand, FIR Diagnostics, 6 Losses
- **ACC6&7**: 4 BPMs, LOLA, EOS, 3 Losses
- **BYP**: 7 BPMs, 1 Toroid, 4 Screens, 1 Wirescanner, 10 Losses
- **COLL**: 6 BPMs, 2 Toroids, 1 Phase, 1 Widerstand, 3 Screens, 2 Wirescanners, 9 Losses
- **SEED**: 4 BPMs, 4 Screens, 1 TEO
- **UND**: 13 BPMs, 7 Wirescanners, 22 Losses
- **FEL BL**: Intensity, Spectrum, Position

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Example: European XFEL

- **Injector**
  - Booster 1: 100 MeV
  - Booster 2: 2 GeV
  - LINAC: 100 Modules
  - Collimator Switchyard
  - 20 GeV
- **Total Length**: 3.3 km

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XFEL: Some Types and Numbers

<table>
<thead>
<tr>
<th>Monitor (Standard Diagnostics Only)</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPMs (cold)</td>
<td>120</td>
</tr>
<tr>
<td>BPMs (Striplines, Pickups)</td>
<td>380</td>
</tr>
<tr>
<td>Charge Monitors (Torids, F-Cups)</td>
<td>40</td>
</tr>
<tr>
<td>Beam Size: OTR, Wirescanners, SR Ports</td>
<td>50</td>
</tr>
<tr>
<td>Dark Current</td>
<td>12</td>
</tr>
<tr>
<td>Loss Monitors (PM Systems, Fibres)</td>
<td>300</td>
</tr>
<tr>
<td>Phase</td>
<td>15</td>
</tr>
<tr>
<td>Other</td>
<td>About 50</td>
</tr>
<tr>
<td>Total</td>
<td>About 1000</td>
</tr>
</tbody>
</table>

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Hotspot: Bunch Compressor

- **TTF2**: 120 MeV
- **XFEL**: 500 MeV
- **Interface between Injector and Main Linac**
  - End of Space Charge Dominated Region
  - Fix/Control Optics between Injector and Main Linac
- **Preparation of the high Peak Current**
  - Control/Optimize the longitudinal Profile
- **BC’s: Most Critical for View of Emittance Blow Up**
  - Measure/Optimize Emittance
  - Access Slice Parameters
  - Move on with well characterized 6 Dim Phase Space

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Hotspot 2:

- **Collimator/Beam Distribution/Undulator**
  - Optics Check/Correction
  - Emittance Control
  - Orbit Fine Tuning -> (fast) Feedbacks
  - Longitudinal/Slice: Difficult/Impossible at 20 GeV
  - Optimize Orbit in Undulator
Hotspot 3: Photon Beamline

- Detector Unit F2 (apertures, detectors, mirror)
  - Intensity + beam profile + diffraction (coherence)
  - Reflection into spectrometer

- Detector Unit F1 (apertures + detectors)
  - Intensity + beam profile
  - Deflection into spectrometer

- MCP detector (Au wire/mesh + MCP)
  - Intensity + beam profile

- Grazing incidence grating spectrometer with intensified CCD
  - Single shot spectrum

- Thick line of detectors for synchrotron radiation
- Beamline for synchrotron radiation from dipole magnet

Standard Electron Beam Diagnostics

- Charge
- Beam Sizes -> Emittance, Matching
- Beam Position -> Orbit, Beamsize
- Losses

Charge Measurement: Toroids

- Single Bunch Resolution ~ 5 \times 10^{-3}
- Measurement Range up to 5 nC (0.5 V/nC)
- Suitable for 9 MHz Bunch Rep. Rate

- In House Development:
  - Single Bunch Resolution ~ 5 \times 10^{-3}
  - Measurement Range up to 5 nC (0.5 V/nC)
  - Suitable for 9 MHz Bunch Rep. Rate

- Single bunch 1.2 nC
- Train of 30 bunches

BPMs (warm)

- About 60 BPMs installed in the TTF LINAC
  - Striplines < 30 µm (single bunch)
  - Installed inside and aligned to the quads
  - Pickups
  - Injector and Bunch Compressor
  - Undulator Pickups < 10 µm (single bunch)
    - 19 stations in and between the 6 undulator segments

Cold BPMs

- 1 per module -> 120 for XFEL
- Development going on
  - Reentrant Cavity BPM (CEA Saclay)
  - Pick up or Button BPM (DESY)
  - Cavity HOMs (SLAC, CEA, DESY)
- Bunch Size and Emittance
  - 3D OTR Screens and 15 WS
  - 4 Cell FeDs Section with 4 Stations (OTR/WS)
  - OTR: Digital Camera System
  - Resolution of 10 µm
  - Network of Triggered and Gated Cameras
  - Collab. of DESY/INFN Frascati/Uni Roma 2
**Emittance Measurements: Screens and Wiresscanners**

- 45° Mirror
- Lens(1)
- Attenuators
- Lens(2&3)
- Digital Camera

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**Phase Monitor**

Principle:
- Isolated impedance-matched Ring Electrode installed in a "thick Flange"
- Broadband, Position independent Signal
- One installed after the Gun, each magnetic Chicane (both BCs, the Collimator + before Undulator)

- BC’s: Energy Fluctuations \(\rightarrow\) Phase Fluctuations
- TOF Measurement: Resolution < 0.2° or 0.4 ps
- Fast timing signals with sub ps resolution

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**Special Electron Beam Diagnostics**

- Longitudinal Diagnostics
- Arrival Time

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**Special Diagnostics Layout @ TTF**

- Injektor II
- CSR Beamline
- Compression Monitor (CDR)
- Lola: Transverse Mode Cavity
- EOS: Sampling Chirped Pulse (Time \(\rightarrow\) Spectrum)
- FIR Baseline
- CTR & CDR
- FIR Diagnostics
- CSR @ Dipole
- CSR @ Diffraction Radiator
- CTR & CDR
- EOS 2 Time \(\rightarrow\) Spatial

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**Bunchlength and Compression**

Requirement: Resolve Structures of 100 fs and less

- **Qualitative:** Optimization of the Compression
  - Emission \(= n^2 \text{ for } \sigma_x < \lambda\)
  - Phase Tuning by maximizing coherent FIR Emission
  - Use of simple Pyro-Detectors in the FIR
  - Useful for Tuning / Feedback (on RF-Phase)

- **Quantitative:** Measurement of Bunch Length
  - Use coherent FIR Radiation and Autocorrelation Methods.
  - Transverse Mode Cavity (Integrated Streak Camera)
  - Electro-Optical-Sampling
  - Optical Replica
  - All are more complicated \(\Rightarrow\) no online Tools (currently)

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**Compression Monitor**

- SR or Diffraction Radiation:
  - coherent power \(= \frac{1}{\sigma_x}\)
  - non interceptive
  - fast, but qualitative measurement
  - Single Bunch Resolution possible
  - Ideal suited to detect relative bunch length changes
  - suited for Feedback on RF Phase (already established at SPPS)

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**Transverse Mode Cavity**

- "Intra Beam Streak Camera"
- Uses direct beam image
- Most straightforward
- Access to
  - Longitudinal Profile
  - Slice Parameters

Under Commissioning:
- Hardware operational
- First Beam Shapes observed
- Results still very preliminary but bunches proved to be extremely short

**Protection Systems**

**Superconducting LINACs vs. Light Sources**

- Losses for sensitive Components need to be small:
  - Detection of Beam Loss to $< 10^{-6}$ Level

<table>
<thead>
<tr>
<th>Lightsource</th>
<th>HERA</th>
<th>TTF</th>
<th>XFEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>2 GeV</td>
<td>27 GeV</td>
<td>1 GeV</td>
</tr>
<tr>
<td>Length/Circumference</td>
<td>200 m</td>
<td>630 m</td>
<td>250 m</td>
</tr>
<tr>
<td>$I^-$</td>
<td>200 mA</td>
<td>50 mA</td>
<td>0.00072 mA</td>
</tr>
<tr>
<td>Charge/Bunch</td>
<td>0.130 μC</td>
<td>1 μC</td>
<td>7.3 μC</td>
</tr>
<tr>
<td>Beam Power</td>
<td>0.4 GW</td>
<td>1.3 GW</td>
<td>7.2 $10^{-5}$ GW</td>
</tr>
<tr>
<td>Dumped Energy</td>
<td>260 J</td>
<td>27 kJ</td>
<td>7.5 kJ @ 10 Hz</td>
</tr>
</tbody>
</table>

**Protection Systems**

- "Passive" Systems
  - Collimators to scrape Dark Current and Halo
  - Gun (transverse)
  - Bunch Compressors (longitudinal)
  - Collimator (transverse & longitudinal)
  - Dark Current kicker @ 5 MHz

- Active Systems
  - Machine Status
    - Slow: Magnets, Valves, Klystrons
    - Fast: Low Level RF
  - Beam Loss Monitor
    - Localized at dangerous Positions
    - Slow (from Train to Train)
    - Fibers/Cables for monitoring larger Sections
  - Acting on
    - Gun-Laser
    - Booster RF Stations
    - Emergency Dump

**Other Energies: Dark Current**

- RF Structures at High Gradient emit Dark Current
  - At high Duty Cycle: $\#$RF/$\#$Laser Buckets: > 260 (TTF currently 1300)
  - Gun gradient will be increased to reduce Emittance
  - (TTF 40 MV/m -> XFEL 60 MV/m)
  - Some Superconducting Cavities might show Field Emission
  - Charge will mostly be spilled close to the source

Dark Current produces: Losses, Activation, Cryogenic Load

**Example: TTF2 Collimator**

- Collimator $\approx$ 20 m
- Energy & Transverse Collimation

**Active: Beam Inhibit System**

- BIS (Beam Inhibit System)
- BIC (Beam Interlock Concentrator)
- Distributed System of OR Gatters
- Viewscreens
- In/out
- Magnet Status
- FEL Line
- Bypass
- Power Supplies
- Vacuum
- Cryogenics
- RF Status
- Machine Status
- Infrastructure

- Reaction Time: Pulse to Pulse
- Reaction time: Within the Bunchtrain ($\sim$3 µs)

- Fast RF Signals
- Sparks, Quench, ...
- Fast Events

- Laser
- Booster RF
- Emergency Dump

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Active Systems

- Reaction Times are dominated by Signal Travel
- Loss of Single Bunches → No Means
- Losses within the Bunch Train
  - About 55 Bunches are in the machine at the same time
  - Interlock Signals have to travel to the Gun to Stop the Beam
- About 80 more bunches leave the Gun during this Time
- Most sensitive Components have to take up to 130 Bunches (2.75 kJ/135µs)
- Or: Need Tools to Stop Beam after the Gun
- Emergency Dump in the Switchyard (600 m to Dump + 1µs for Kicker)

Injektor II
Injektor I
Booster #1
3rd Harm.
XSIN
XSE
50 m
80 m
500 MeV
Collimator Switchyard
Ca. 150 m
Ca. 120 m
Ca. 270 m
Ca. 400 - 500 m
XS1
0 m
100 MeV
c.a. 1150 m
SASE I
Dump I
Photon Beamline
SASE II
Undulator I
Undulator I I
LINAC Modules
Booster #2
2 GeV
Bunch Compressor BC1
Bunch Compressor BC2
20 GeV

Transmission Based Protection System for TTF2

<table>
<thead>
<tr>
<th>Dev.</th>
<th>Name</th>
<th>Dev.</th>
<th>Name</th>
<th>Z-Position</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Toroidal/Blue</td>
<td>T9</td>
<td>Toroidal/Blue</td>
<td>1.29 m</td>
<td>PEL Beamline, total length</td>
</tr>
<tr>
<td>T2</td>
<td>Toroidal/Blue</td>
<td>T10</td>
<td>Toroidal/Blue</td>
<td>1.25</td>
<td>Bypass Beampath, total length</td>
</tr>
<tr>
<td>T3</td>
<td>Toroidal/Blue</td>
<td>T11</td>
<td>Toroidal/Blue</td>
<td>0.548 m</td>
<td>Make sure beam reaches the dump (PS, Beamline)</td>
</tr>
<tr>
<td>T4</td>
<td>Toroidal/Blue</td>
<td>T12</td>
<td>Toroidal/Blue</td>
<td>20.548 m</td>
<td>Make sure beam reaches the dump (PS, Beamline)</td>
</tr>
<tr>
<td>T5</td>
<td>Toroidal/Blue</td>
<td>T13</td>
<td>Toroidal/Blue</td>
<td>3.548 m</td>
<td>Make sure beam reaches the dump (PS, Beamline)</td>
</tr>
</tbody>
</table>

Make sure beam reaches the dump (Bypass)
Ca. 248.9 m Toroid/? Dump
T10 20.548 m Toroid/2 UB C2 T2
Make sure beam reaches the dump (FEL Beamline)
Bypass Beampath, total length
161.254m Toroid/16 Bypass T1 11.25 m Toroid/3 Gun T1
Make sure beam reaches the dump (FEL Beamline)
Ca. 248.9 m Toroid/12 Exp T9 1.25 m Toroid/3 Gun T1
Make sure beam reaches the dump (FEL Beamline)

In Collaboration with CEA, Saclay

Loss Monitor System TTF2

≈ 60 Fast Loss Monitors (Photomultipliers) at critical Positions

Which photon beam parameters are required?

- Spectrum
  - spikes ⇒ modes, pulse length
  - wavelength ⇒ electron energy tuning for experimental needs
- Intensity
  - SASE optimisation, statistics, saturation, normalisation
- Position & Profile
  - stabilisation and focusing
- Timing
  - pump-probe experiments

All these Parameters are required for Machine Operation AND User Experiments, furthermore, the Users need these Information on-line, non-destructive, and time-resolved!

Spectral Properties

- Requirements
  - Online Measurement Bunch to Bunch
  - Single Bunch Resolution
  - Non Destructive
  - High Resolution $\Delta E / E = 10^{-6}$
- We have Solutions for VUV
- XRAY needs R&D

On-line VLS grating spectrometer

- use grating as mirror
- reflect only some percent into 1st order and about 80% in 0th order towards experiment
- main challenge: line detector readout at 1 MHz
The energy of the undulator and the beam profile will be monitored with the Laue crystal and one or more CCD camera heads directly connected to the vacuum vessel via fibre optic tapers and/or channel plate amplifiers.

No commercial, calibrated detectors available!

MCP Diagnostics Unit

- large dynamic range (~7 orders of magnitude)
- can be scanned to measure beam position and profile
- will not survive long pulse trains
- the wire produces unwanted diffraction

Reference number at the German Patent Office: 102 44 303

Gas-Monitor Detector for Monitoring VUV and EUV Free-Electron-Laser Radiation

Single photoionisation:

\[ N = N_{ph} \times n \times \sigma \times l \]

\( N \) = number of electrons or ions
\( N_{ph} \) = number of photons
\( n \) = target density
\( \sigma \) = photoionisation cross section
\( l \) = length of interaction volume

6 x 10^{12} VUV photons at 87 nm (\( h\omega = 14.3 \ eV \)) within a photon pulse of 100 fs:

⇒ pulse energy: 14 \( \mu \)J
⇒ peak power : 140 MW

Photon Beam Position

Accuracy for on-line of relative beam positions:

= 25 \( \mu \)m

Reference number at the German Patent Office: 102 44 303

Conclusion

- TTF2/VUV FEL is real prototype for XFEL Diagnostics
- Many systems are already available, but need
  - Upgrade
  - Scaling
  - Improvements
- But there are still R&D needs
  - Longitudinal diagnostics
  - Arrival Time (Synchronisation)
  - Online Spectral Properties

Thanks!
To all Colleagues who provided
Material for this Talk!