TESLA Test Facility

XFEL Electron and Photon Diagnostics

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Sino-German Center for Research Promotion
Bejing, May 11th-13th, 2005

Outline

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

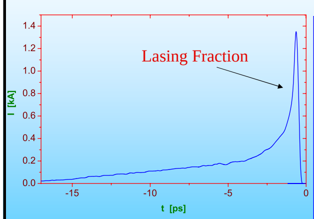
Requirements

- 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

LINAC - Storage Rings

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

... further Complication



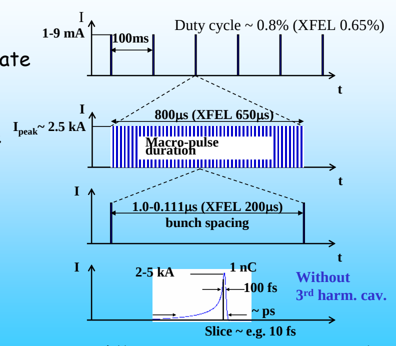
Longitudinal Charge Distribution at TTF („Femtosecond Mode“)

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 !

Time Structure of Superconducting Linacs

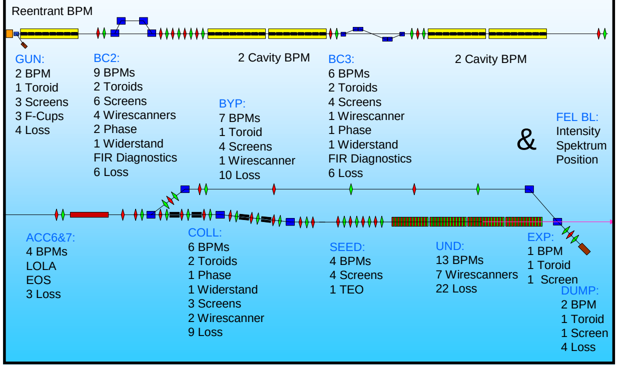
- Repetition rate
- Macro-pulse
- Bunch
- Slice



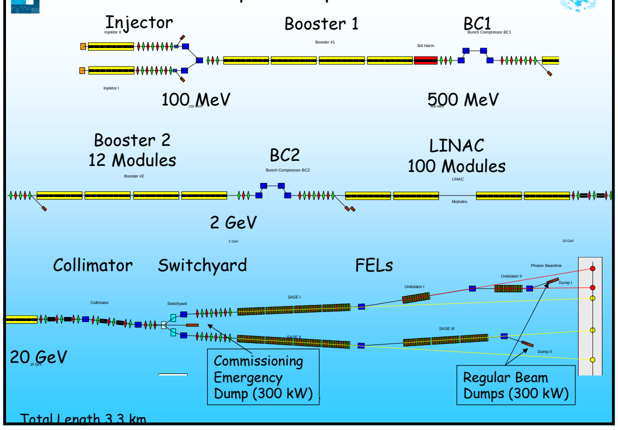
Distribution of Diagnostics

- LINAC
  - Gun determines Beam Quality, later it gets only worse
  - Beam Quality is vulnerable by Space Charge at low Energy
  - BC´s introduce Emittance Heating and Instabilities
  - Beam gets more stiff (-> predictable) during acceleration
- 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

Example:
VUV FEL/ TTF2



Example: European XFEL

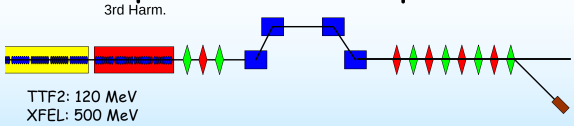


XFEL: Some Types and Numbers

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

TTF2: about 200 devices

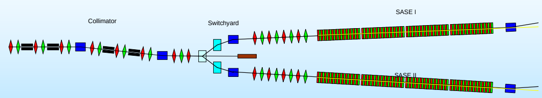
Hotspot: Bunch Compressor



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

Hotspot 2:
Collimator/Beam Distribution/Undulator



- Optics Check/Correction
- Emittance Control

} Wirescanners with appr. Phase Advance

- Orbit Fine Tuning -> (fast) Feedbacks
- Longitudinal/Slice: Difficult/Impossible at 20 GeV ☹
- Optimize Orbit in Undulator

Hotspot 3:Photon Beamline

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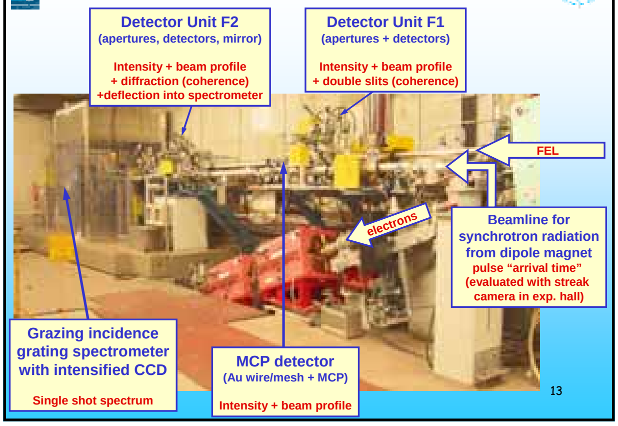

13

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Standard Electron Beam Diagnostics

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

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Charge Measurement: Toroids

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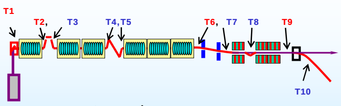
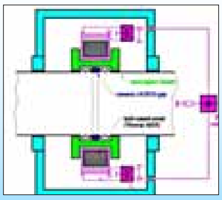
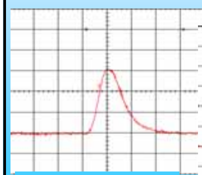
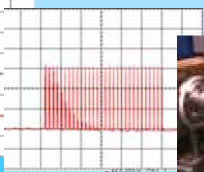




In House Development:
- Single Bunch Resolution ~ 5 10^{-3}
- Measurement Range up to 5nC (0.5V/nC)
- Suitable for 9 MHz Bunch Rep. Rate



Single bunch 1.2 nC



Train of 30 bunches

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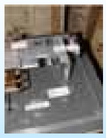
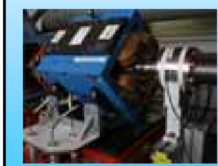
BPMs (warm)





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

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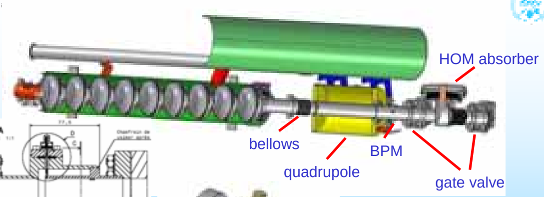
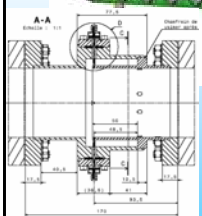
Cold BPMs





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)

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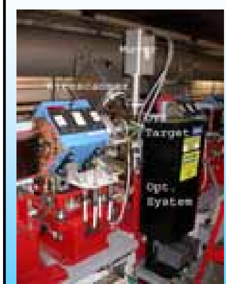
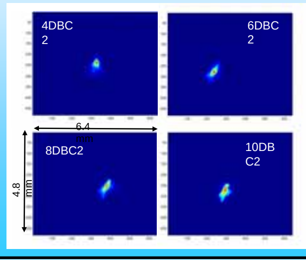
Emittance Measurements: Screens and Wirescanners

Bunch Shape and Emittance
- 30 OTR-Screens and 15 WS
- 4 Cell FoDo 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





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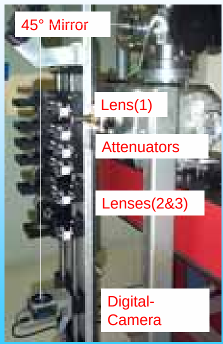
Emittance Measurements: Screens and Wirescanners



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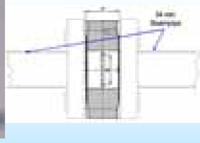
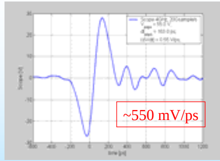
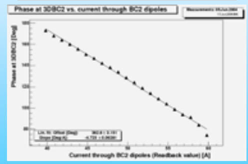
Phase Monitor





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 -> Phase Fluctuations
  TOF Measurement: Resolution < 0.2° or 0.4 ps
- Fast timing signals with sub ps resolution

20

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Special Electron Beam Diagnostics

- Longitudinal Diagnostics
- Arrival Time
- .....

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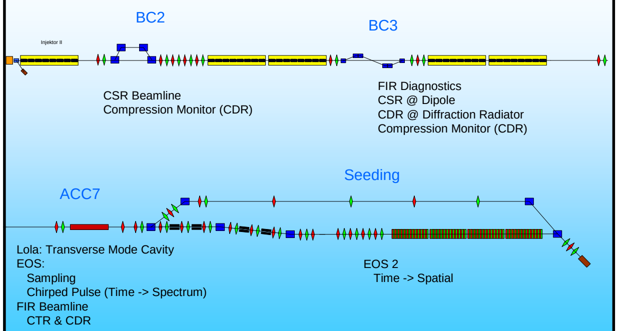
Special Diagnostics Layout @ TTF



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Bunchlength and Compression

Requirement: Resolve Structures of 100 fs and less

- Qualitative: Optimization of the Compression
  - Emission ≈ n² for $\sigma_s \leq \lambda$
    - 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 -> no online Tools (currently)

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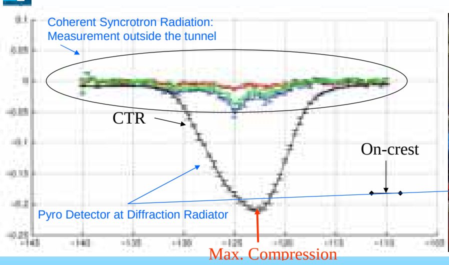
Compression Monitor



SR or Diffraction Radiation:

- coherent power ~ $1/\sigma_z$
- non interceptive
- fast, but qualitative measurement
- Single Bunch Resolution possible

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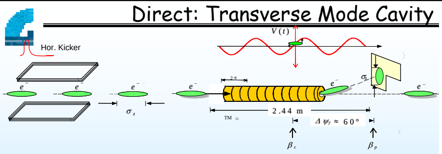
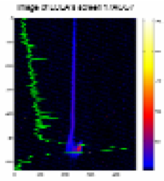
⇒ ideal suited to detect relative bunch length changes
⇒ suited for Feedback on RF Phase (already established at SPPS)

Direct: Transverse Mode Cavity





LOLA IV in the TTF2-Tunnel

Transverse Mode Cavity ☺
- „Intra Beam Streak Camera"
- Uses direct beam image
- Most straight forward
- 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

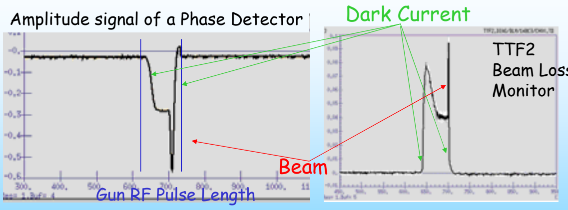
Superconducting LINACs vs. Light Sources

	Lightsource	HERA	TTF	XFEL
Energy	2 GeV	27 GeV	1 GeV	20 GeV
Length/ Circumference	200 m	6300 m	250 m	3300 m
<I>	200 mA	50 mA	0.00072 mA	0.00033 mA
Charge/Fill/Bunch Train	0.130 μC	1 μC	7,2 μC	3.3 μC
Beam Power P = <I> E	0.4 GW	1,3 GW	$7.2\ 10^{-5}$ GW	$6.6\ 10^{-4}$ GW
Dumped Energy /Fill /Bunch Train	260 J	27 kJ	7.2 kJ @ 10 Hz	66 kJ @ 10 Hz

Losses for sensitive Components need to be small:

->Detection of Beam Loss to < 10^{-6} Level !?

Other Energies: Dark Current



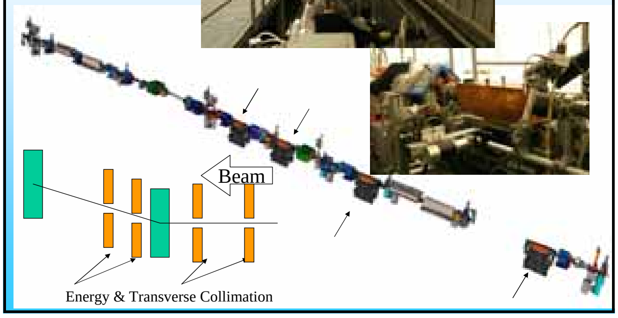
Rf Structures at High Gradient emit Dark Current
- At high Duty Cycle: #RF/#Laser Buckets: > 260 (TTF currently 1300)
- Gun Gradient will be increased to reduce Emittance
  - (TTF 40 MV/m -> XFEL 60 MV/m)
- Some Superconducting Cavities might show Field Emission
  - Charge will mostly be spoiled close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

Dark Current produces: Losses, Activation, Cryogenic Load

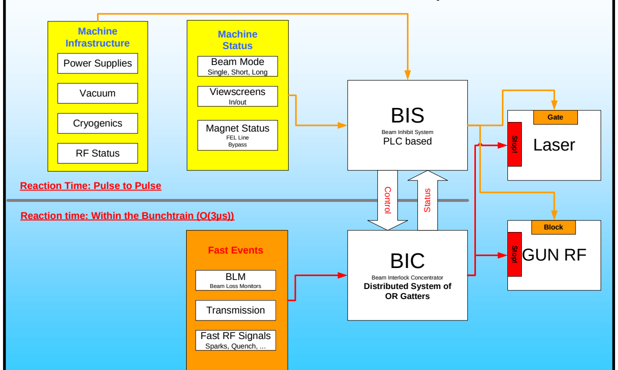
Protection Systems

- "Passive" Systems
  - Collimators to scrape Dark Current and Halo
    - Get rid of Halos/Dark Current as Soon as possible
    - Gun (transverse)
    - Bunch Compressors (longitudinal)
    - Collimator (transverse & longitudinal)
  - Dark Current Kicker @ 5MHz (?)
- Active Systems
  - Machine Status
    - Slow: Magnets, Valves, Klystrons
    - Fast: Low Level RF
  - Beam Loss Monitors
    - Localized at dangerous Positions
    - Fast (within Bunch Train)
    - Slow (From Train to Train)
    - Fibers/Cables for monitoring larger Sections
  - Acting on
    - Gun-Laser
    - Booster RF Stations
    - Emergency Dump

Example: TTF2 Collimator ≈ 20 m



Active: Beam Inhibit System



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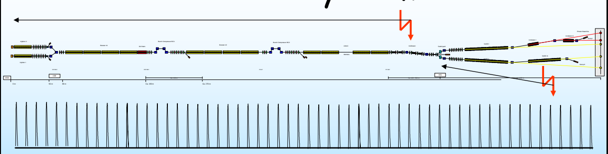
Active Systems



- 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
    - By stopping the Laser
  - – 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) (up to 30 Bunches, < 1 kJ/10μs)

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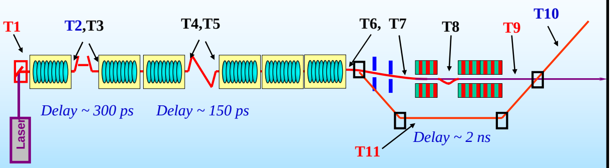
Transmission Based Protection System for TTF2



Dev.	Name	Z-Position	Dev.	Name	Z-Position	Comment
T1	Toroid/3Gun	1,25 m	T9	Toroid/12Exp	244,97m	FEL Beamline, total length
T1	Toroid/3Gun	1,25	T11	Toroid/16Byp	161,254m	Bypass Beampath, total length
T2	Toroid/2UBC2	20,548 m	T10	Toroid/?Dump	Ca. 248,9 m	Make sure beam reaches the dump (FEL Beamline)
T2	Toroid/2UBC2	20.548 m	T10	Toroid/?Dump	Ca. 248,9 m	Make sure beam reaches the dump (Bypass)

32

In Collaboration with CEA, Saclay

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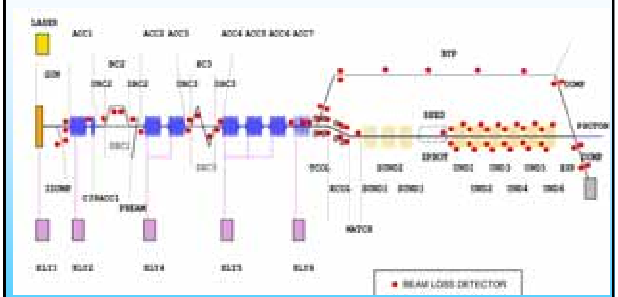
Loss Monitor System TTF2



≈ 60 Fast Loss Monitors (Photomultipliers) at critical Positions

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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 !

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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

VUV Example: TTF2

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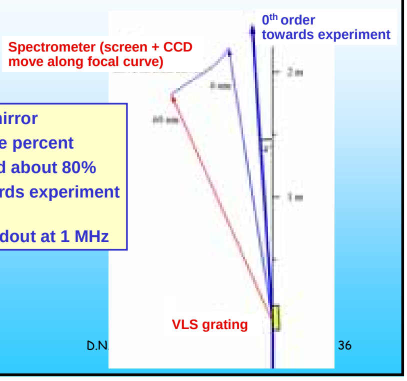
On-line VLS grating spectrometer



- 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

XRAY Ideas

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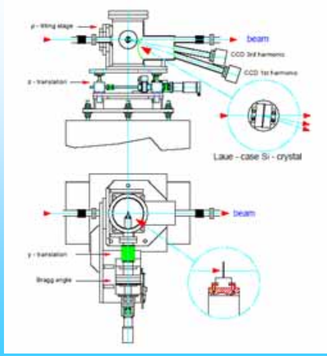
Photon Diagnostic Station: Energy and Profile



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.

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Requirements for Intensity Detectors

- cover full dynamic range: ~ 7 orders of magnitude from spontaneous emission to SASE in saturation
- on-line detectors (non-destructive) for single-pulse measurements (response < 100ns)
- low degradation under radiant exposure
- ultra-high vacuum compatibility

No commercial, calibrated detectors available!

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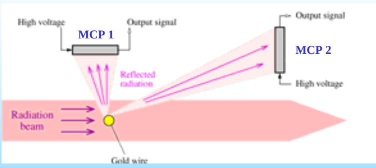
MCP Diagnostics Unit



+ 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

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O.Brovko, A. Fateev, M.Yurkov et al., JINR Dubna

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

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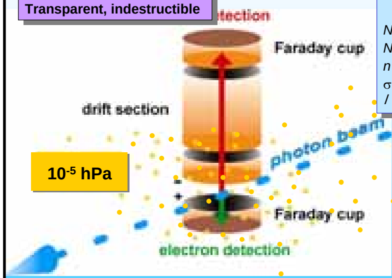
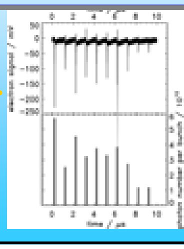
Low particle density => Transparent, indestructible



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
- σ = photoionisation cross section
- l = length of interaction volume



Reference number at the German Patent Office: 102 44 303

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Time Resolved Gas-Monitor Detector Signal from Free-Electron-Laser Radiation at 87 nm (TTF 1)

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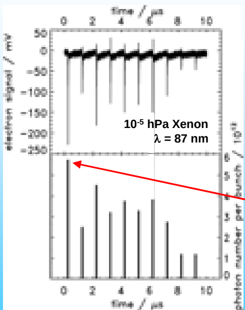

6 x 10¹² VUV photons at 87 nm ($\hbar\omega$ = 14.3 eV) within a photon pulse of 100 fs:

⇒

pulse energy: 14 µJ

peak power : 140 MW

M. Richter, A. Gottwald, U. Kroth, A.A. Sorokin, S.V. Bobashev, L.A. Shmaenok, J. Feldhaus, Ch. Gerth, B. Steeg, K. Tiedtke, R.Treusch, Appl. Phys. Lett. 83, 2970 (2003)

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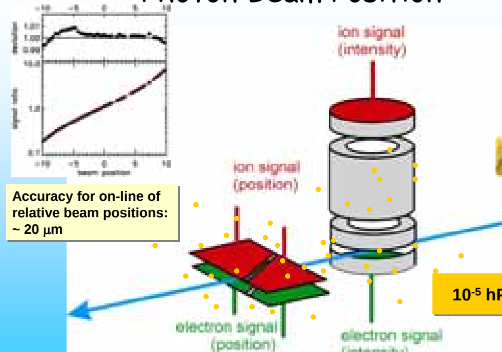
Photon Beam Position



Accuracy for on-line of relative beam positions: ~ 20 µm

Four TTF 2 Gas-Monitor Detectors for Online Intensity and Beam Position Measurements

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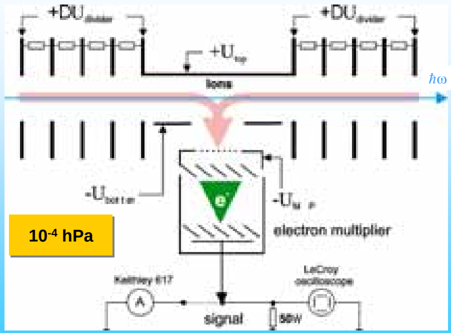
Extended Gas-Monitor Detector Version for Ultra-short X-ray Pulses



PTB

For SPPS, SLAC

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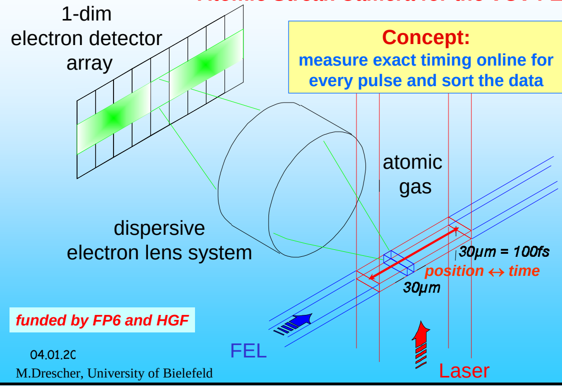
Single-shot cross correlator

Atomic Streak Camera for the VUV FEL

Concept:
measure exact timing online for every pulse and sort the data



funded by FP6 and HGF

04.01.2C

M.Drescher, University of Bielefeld

TESLA Test Facility

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

04.01.2006 D.N. 45

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Thanks !
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04.01.2006 D.N. 46