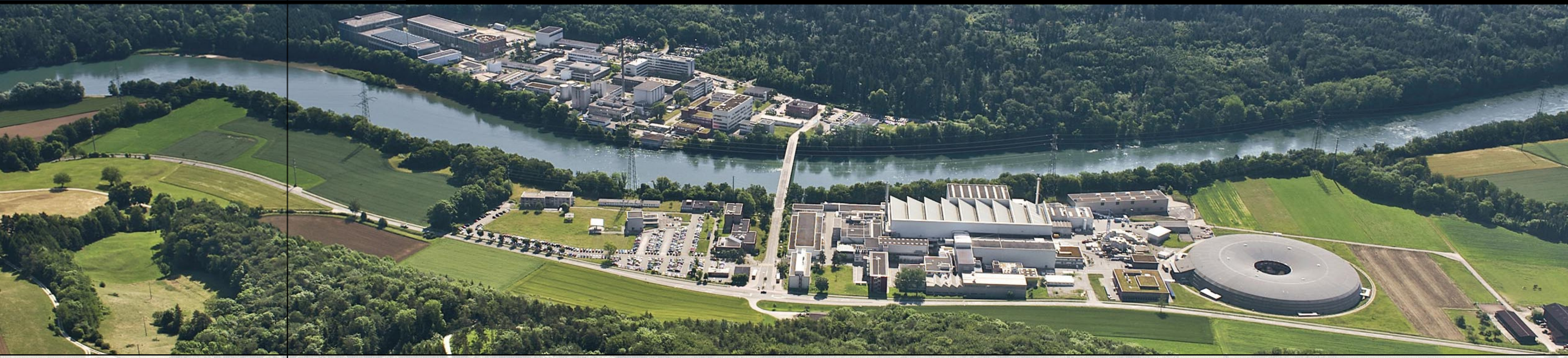
PAUL SCHERRER INSTITUT



Wir schaffen Wissen – heute für morgen

Paul Scherrer Institut

Volker Schlott for the PSI Diagnostics Section

SwissFEL Diagnostics: Overview and Status

(a selection of topics, motivated by the main challenges of the SwissFEL beam parameters)

What will be presented in this talk…:

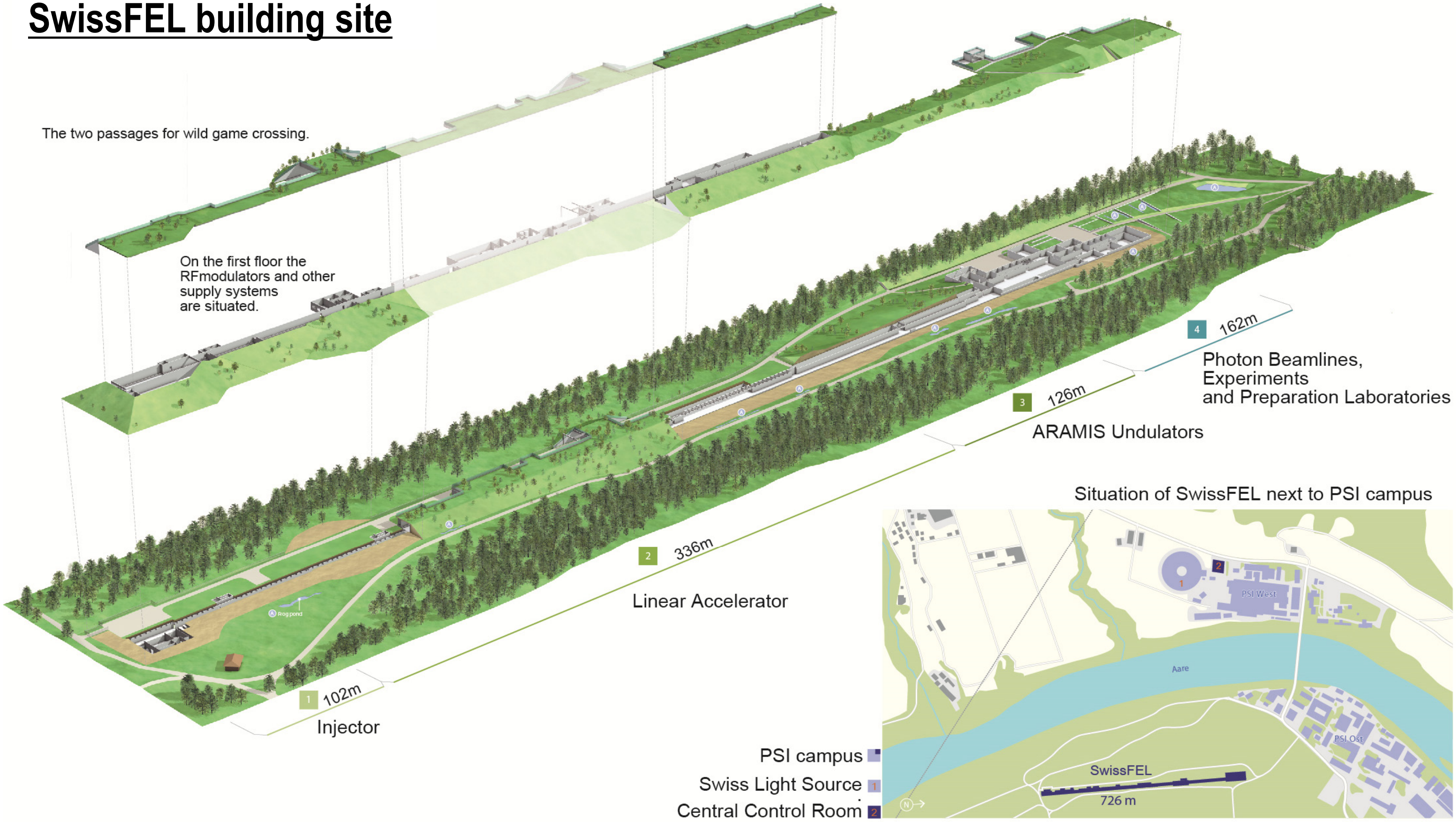
- SwissFEL Status and Diagnostics Requirements
- Beam Position Monitors
- Screen Monitors
- Compression Monitors
- Electron Beam and Laser Arrival Time Monitors
- Status, Conclusions & Outlook

…and much more can be discussed during
coffee breaks, lunch and when having a beer ☺

SwissFEL – a “compact” hard X-ray FEL @ PSI, Switzerland

→ **building length: 726 m** → **construction period: 2012 – 2017**

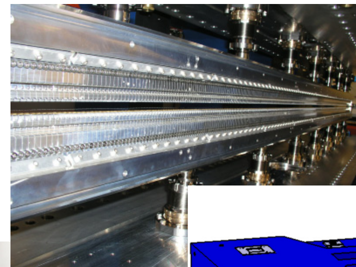
SwissFEL building site

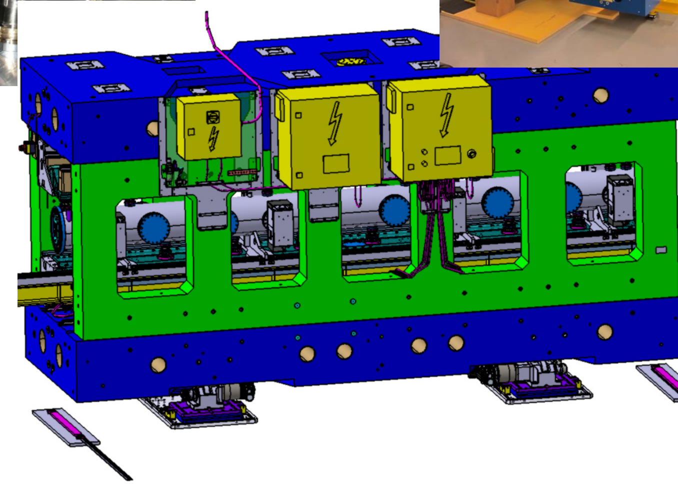


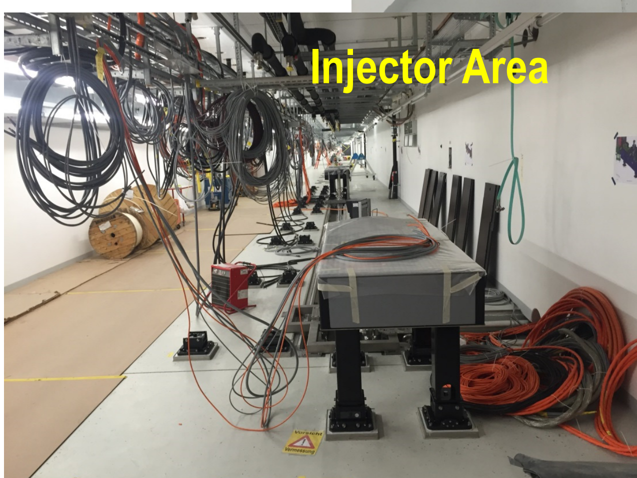
SwissFEL – Building Progress

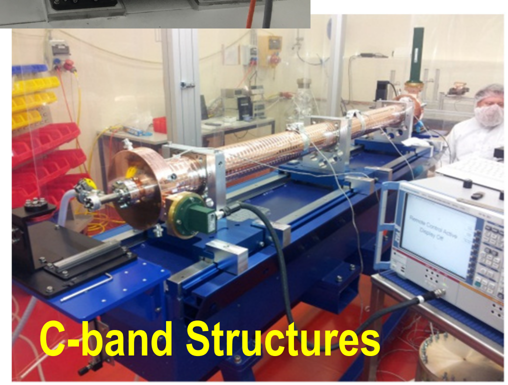
SwissFEL – Progress with Installation & Key Components (August 2015)

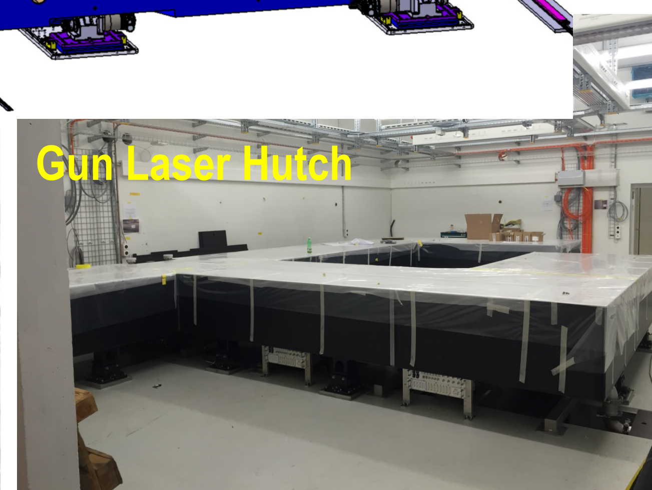
Undulator Assembly











SwissFEL Diagnostics Challenges – Key Beam Parameters

→ low charge (10 pC) capability for all diagnostics monitors

→ high bandwidth pick-ups and detectors to accommodate for 2-bunch mode ($\Delta\tau$ = 28 ns)

→ low emittance beam ($\varepsilon_n \geq$ 180 nmrad) generating small transverse beam sizes

→ ultra-short bunches (2.5 fs < τ < 20 fs) and high compression factors

→ ultra-low synchronization and timing (as well as RF) jitter tolerances

→ all monitors must be capable of being used in (beam-based) real-time feedbacks

SwissFEL Key Parameters	Operation Modes	
	Long Bunch	Short Bunch
Photon Energy	0.2 – 12 keV (1 Å)	0.2 – 12 keV (1 Å)
Power / Energy	60 µJ / 2 GW	3 µJ / 0.6 GW
Electron Energy	5.8 GeV (for 1 Å)	5.8 GeV (for 1 Å)
Bunch Charge	200 pC	10 pC
Rep. Rate	100 Hz	100 Hz
Bunch Distance	28 ns (2 bunches)	28 ns (2 bunches)

SwissFEL Key Parameters	Operation Modes	
	Long Bunch	Short Bunch
Bunch Length	20 fs (rms)	2.5 fs (rms)
Comp. Factors	125	240
Norm. $\varepsilon_{h,v}$	430 nmrad	180 nmrad
Timing Stability	Jitter	Drift
Sync. System	< 10 fs	< 20 fs / day
Bunch Arrival	< 10 fs	< 10 fs / day

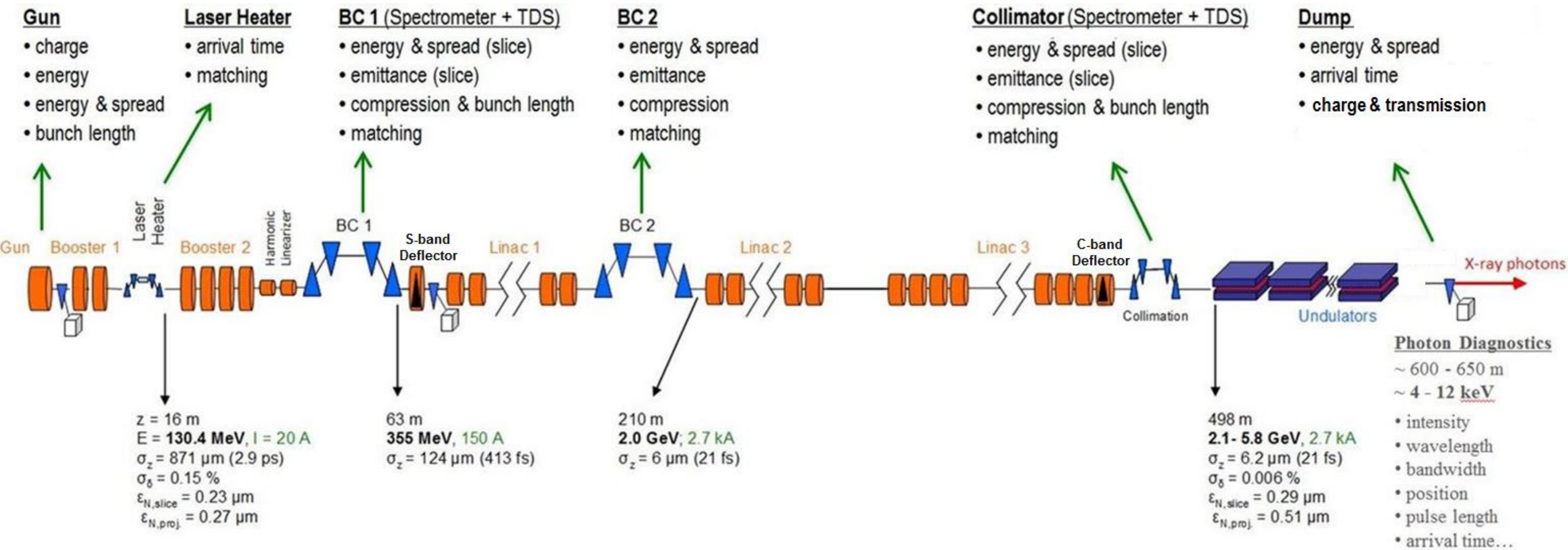
SwissFEL Diagnostics – Schematic Overview

→ **BPMs, loss, charge and transverse profile monitors** are distributed along the accelerator

→ full phase space characterization (**projected parameters**) and **non-invasive longitudinal diagnostics** monitors behind gun and BC-2

→ full phase space characterization with **S-band and C-band TDS** (**sliced parameters**) and **non-invasive longitudinal diagnostics** monitors behind BC-1 and ARAMIS collimator

→ fully equipped **ARAMIS photon diagnostics** for measurement of SASE parameters

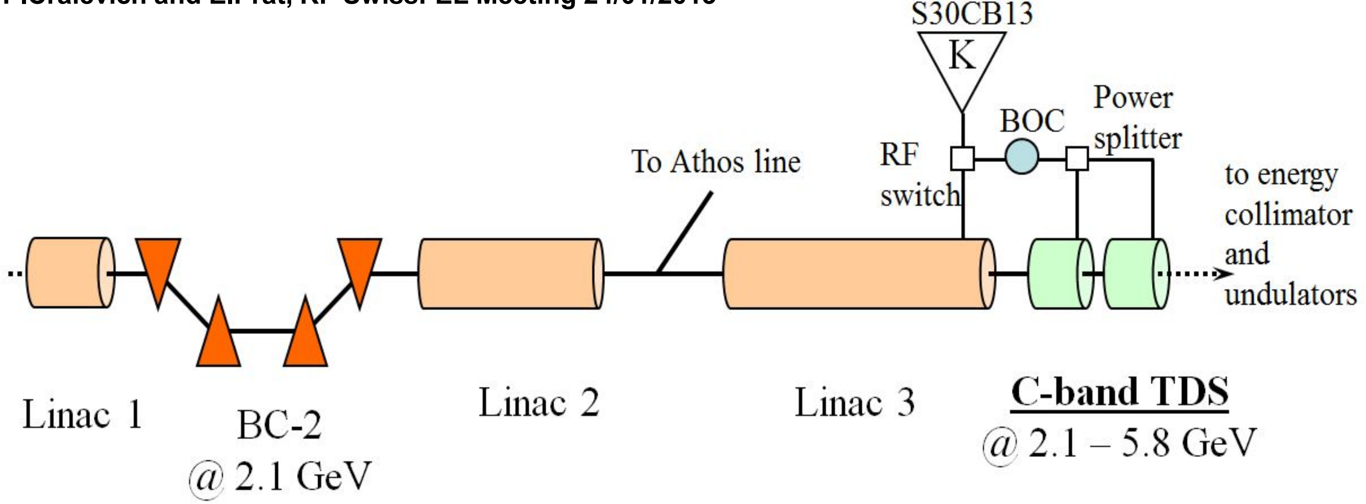


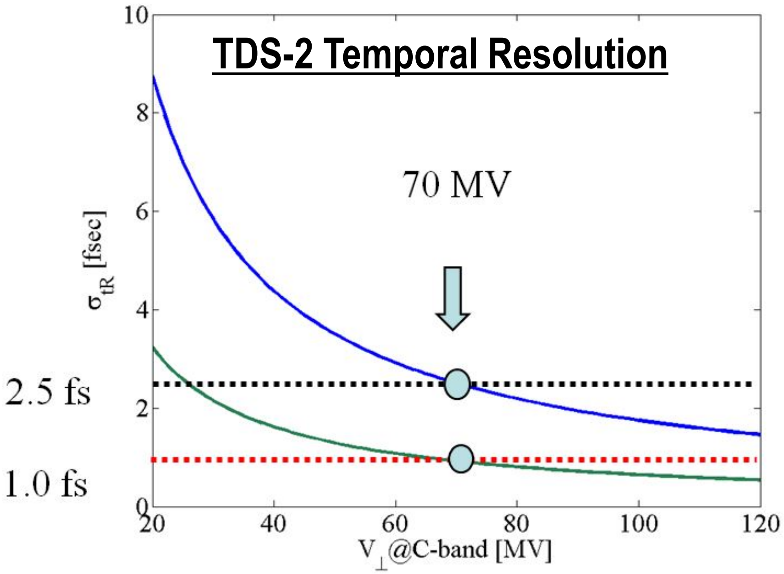
Overview of SwissFEL Diagnostics Components (Phase-1 ARAMIS)

→ Beam Position Monitors:	7 x BPM-38 / 111 x BPM-16 / 27 x BPM-8 (all cavity-type BPMs)
→ Screen Monitors:	10 x high sensitivity, high resolution SCM for meas. at 100 Hz 14 x SCM for observation and control room support at 10 Hz
→ Wire Scanners:	23 x WSC along LINACs, TLs and ARAMIS Undulator
→ Synchrotron Radiation Monitors:	1 x BC-1 / 1 x BC-2 / 1 x Collimator (10^{-4} energy spread res.)
→ Beam Charge Monitors:	4 x Turbo-ICT & BCM-RF (~ 4 % absolute) 145 x BPMs (0.1% relative)
→ Beam Loss Monitors:	38 scintillating monitors (high sensitivity) 8 distributed Cerenkov monitors
→ Dose Rate Monitors:	32 Rad FET dose rate monitors (FERMI-type)
→ Bunch Arrival Time Monitors:	4 x BAMs (in front of LH, BC-2 & collimator, behind ARAMIS undulator)
→ Gun Laser Arrival Time Monitor:	1 x LAM at photo-injector gun
→ Compression Monitors:	1 x BC-1 (THz) / 1 x BC-2 (FIR) / 1 x Collimator (FIR to visible) 2 coherent diffraction radiation monitors (for commissioning)
→ Transverse Deflectors:	1 x S-band (behind BC-1 at 450 MeV providing 15 fs time resolution) 1 x C-band (behind LINAC-3 at 5.8 GeV providing ~ 2 fs time resolution)

Conceptual Design for SwissFEL C-band TDS-2 @ 2.1 and 5.8 GeV

P.Craievich and E.Prat, RF SwissFEL Meeting 24/01/2013





Solution for SwissFEL C-band Deflector

RAIDEN (RAcetrack-shaped Iris-coupling DEflectioN structure): high gradient C-band deflecting structure for SACLA developed by MHI

References for RAIDEN: H. Ego et al., IPAC11

Blue line: E = 5.8 GeV, β_d = 30 m, Q = 200 pC, ε = 0.4 mm mm rad
Green line: E = 2.1 GeV, β_d = 60 m, Q = 10 pC, ε = 0.3 mm mm rad

Modular Topology of SwissFEL Diagnostics Systems

Examples of PU & Detectors

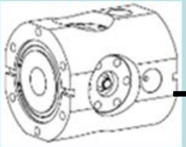
Cavity BPM

Button BPM

Schottky diode

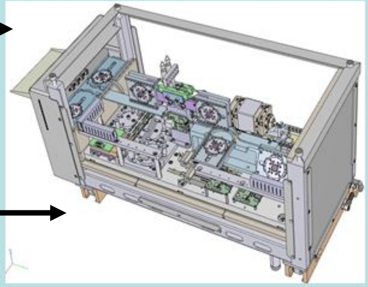
Turbo ICT

BAM pick-up



LAM PD

EO BAM / LAM Front Ends



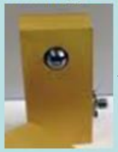
Modular Topology of SwissFEL Diagnostics Systems

Examples of PU & Detectors

Cavity BPM

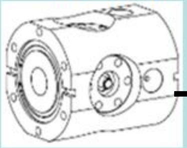
Button BPM

Schottky diode



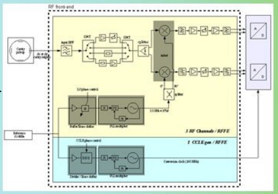
Turbo ICT

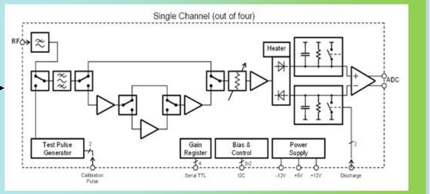
BAM pick-up



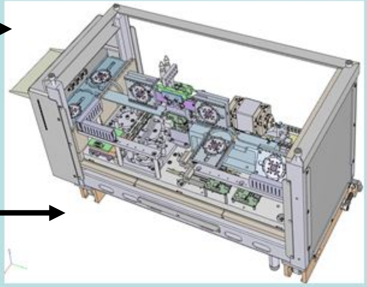
LAM PD

Front Ends (specific / generic)

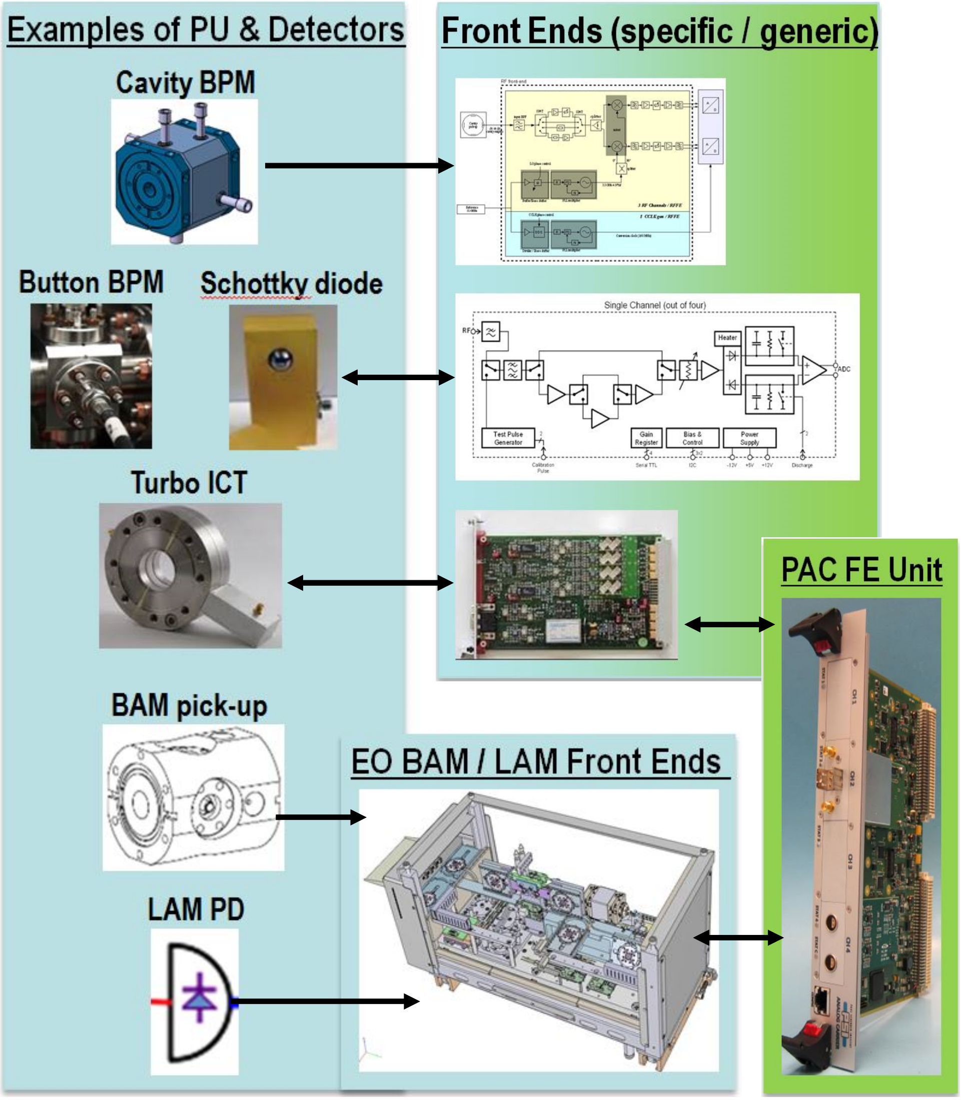




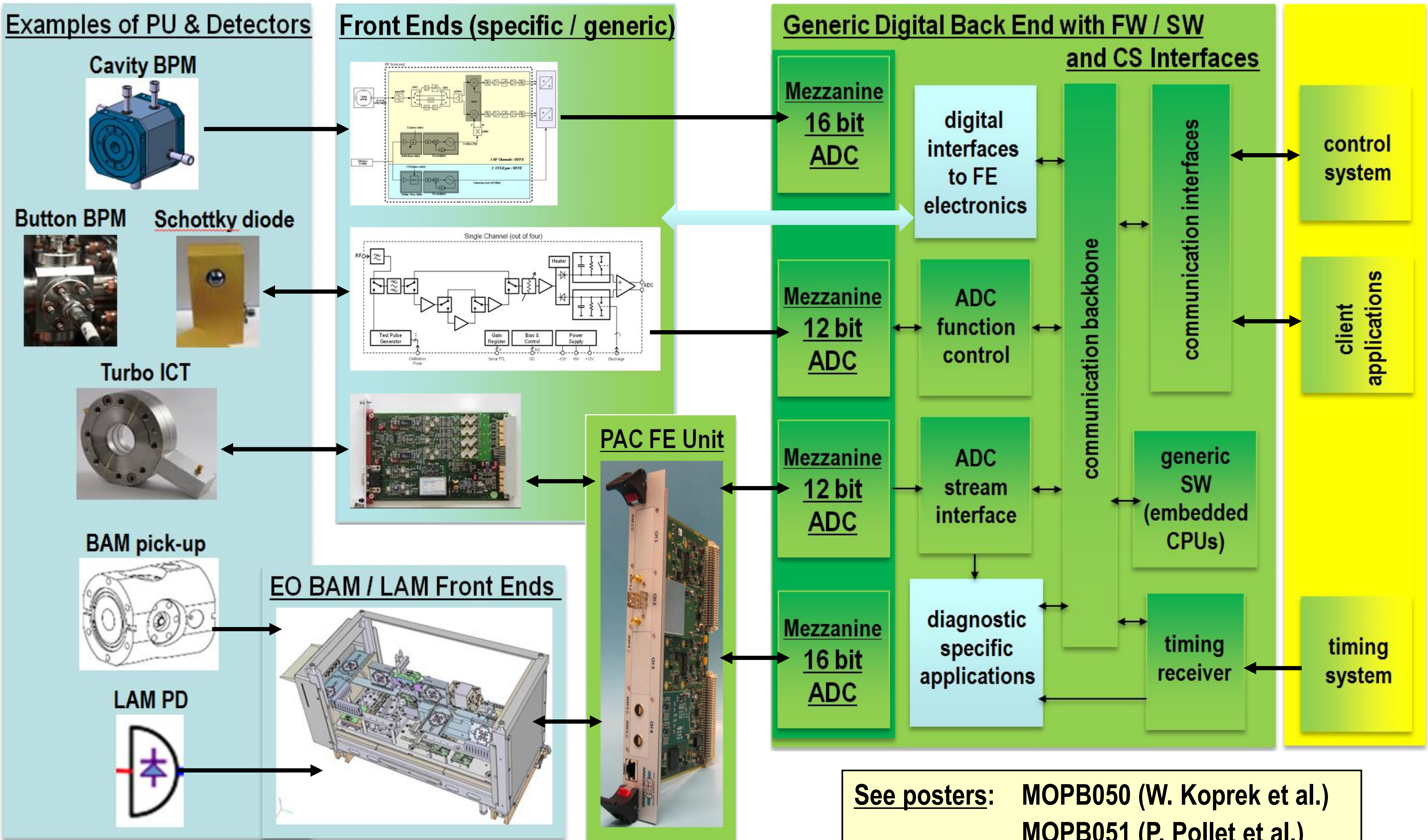
EO BAM / LAM Front Ends



Modular Topology of SwissFEL Diagnostics Systems



Modular Topology of SwissFEL Diagnostics Systems



See posters: MOPB050 (W. Koprek et al.)
MOPB051 (P. Pollet et al.)

SwissFEL Beam Position Monitor System

Parameter	Injector, Linac, TL		Undulators
Pickup Name (Number = Aperture in mm)	BPM38	BPM16	BPM8
Pickup Length	250 mm	100 mm	100 mm
Resonant Frequency	3.2844 GHz	3.2844 GHz	4.9266 GHz
Quality factor	40 (low-Q)	40 (low-Q)	1000 (high-Q)
Quantity Installed in Machine (Phase 1)	7	111	27
Position Range*	±10 mm	±5 mm	±1 mm
RMS Position Noise	<10 µm	<5 µm	<1 µm
Position Drift (per week)	<10 µm	<5 µm	<1 µm
Relative RMS Charge Noise	<0.1%	<0.1%	<0.1%
# Bunches per Train	1-3 (Test: SITF 1-2)		1
Min. Bunch Spacing	28 ns		-

BPM Electronics: based on PSI design for European XFEL, but optimized for low charge and short (28 ns) bunch distance using latest FPGA technology (Kintex-7/Artix-7)

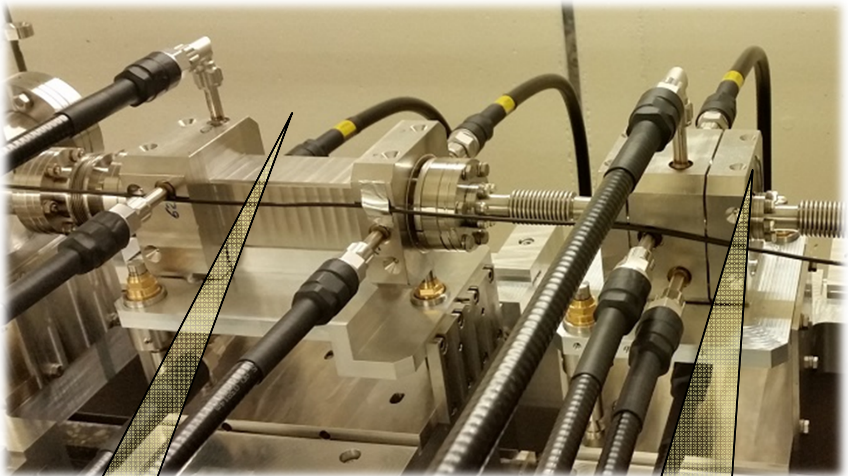
LINAC: IQ downconversion to base-band, digital post-processing & LO phase feedback, ...

Undulator: IQ downconversion to IF, digital and further downconversion to base-band.

Beam Tests: sub-µm position resolution and ~ 10 fC charge noise

SwissFEL Beam Position Monitor System

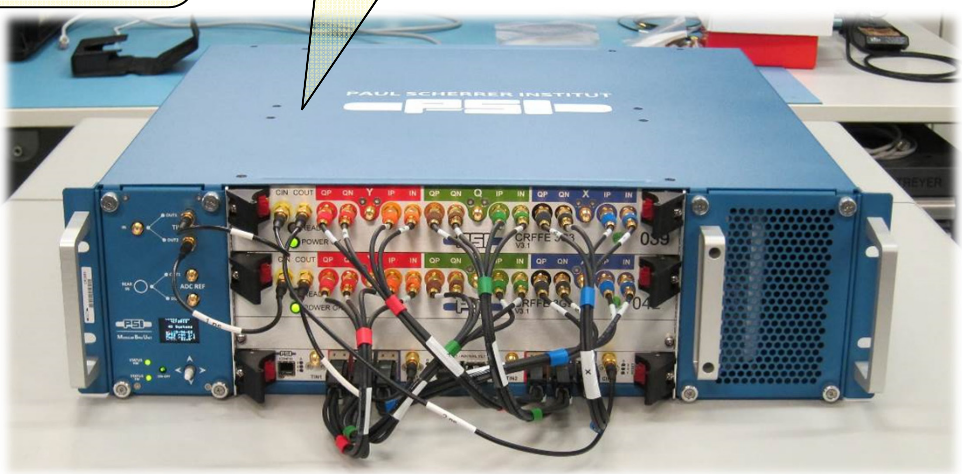
See poster TUPB065 (B. Keil et al.)



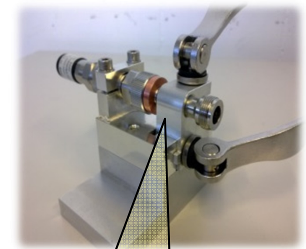
BPM38 (stainless steel)

Electronics (BPM16+38)

BPM8 (copper-steel hybrid)

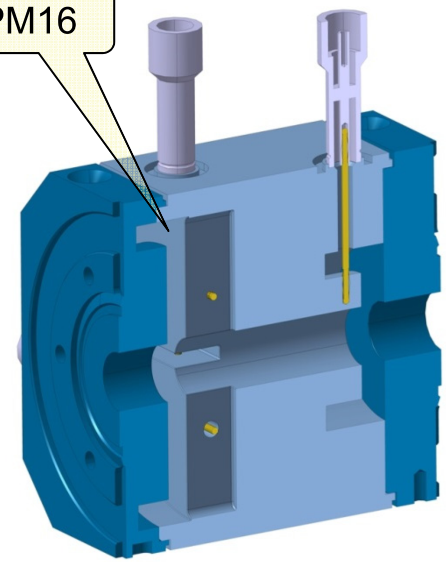


Feedthrough: PSI design, produced in CH (BC-Tech).



Feedthrough Test Adapter

BPM16



SwissFEL Transverse Profile Imager (design by Rasmus Ischebeck)

1st choice: scintillating screen monitors

→ 2d imaging of transverse beam profile information

→ direct measurement of beam optics and matching

→ efficient determination of transverse emittances (quad scans during machine set-up)

→ direct meas. of bunch length & sliced beam parameters (TDC, dipole magnet)

2nd choice: wire scanners (not shown in detail within this presentation)

→ 1d imaging of transverse beam profile information

→ COTR back-up for screen monitors (should not be required anymore!)

→ online and quasi non-destructive measurement of transverse beam profiles and emittances by continuous scanning in LINAC (4 WSC at 90° phase advance)

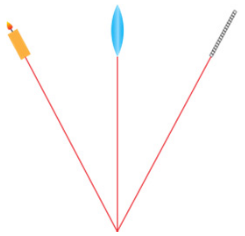
Design Goals for Scintillating Screen Monitors

- sufficient spatial resolution for measurement of sub-micron emittances at low charges
- avoid coherent transition radiation from highly brilliant electron beams

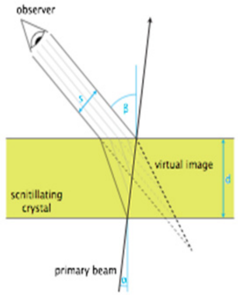
SwissFEL Transverse Profile Imager (design by Rasmus Ischebeck)

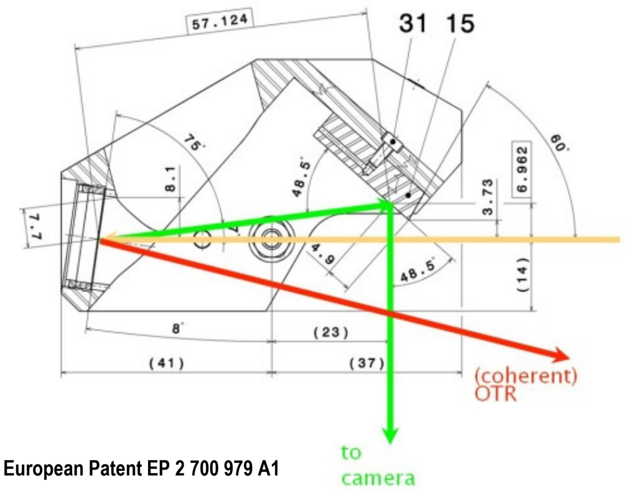
Design Principles

- entire screen (large RoI) can be observed without depth-of-field issues by following Scheimpflug imaging principle
- detector (CMOS sensor) is tilted by 15° for 1:1 imaging to avoid astigmatism

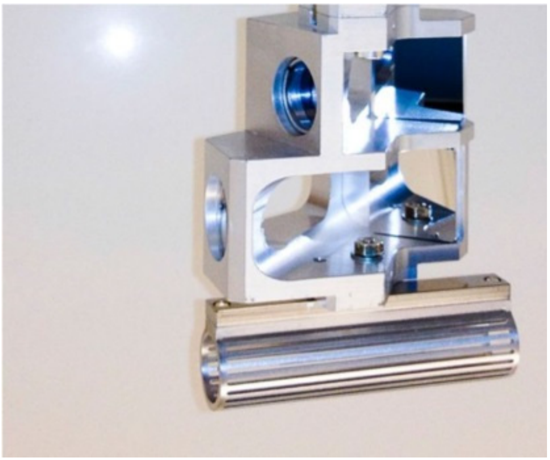


- use YAG or LuAG scintillator crystals instead of OTR
- observation of beam profile according to Snell's law of refraction
- beams can be imaged, which are smaller than scintillator thickness





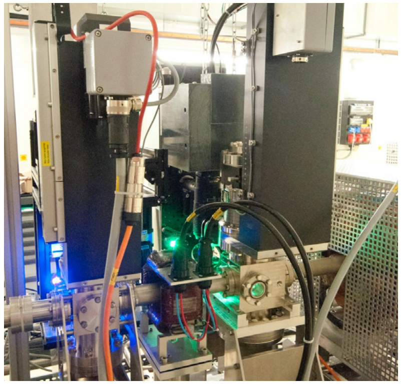
European Patent EP 2 700 979 A1



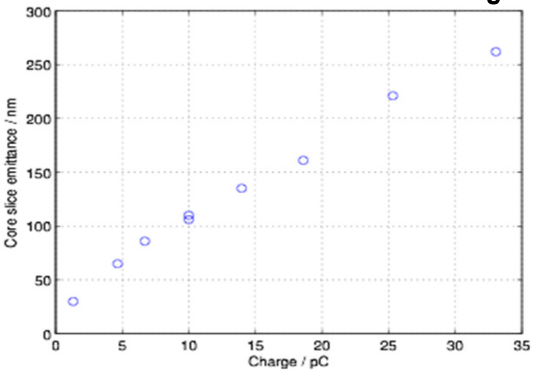
SwissFEL Transverse Profile Imager (design by Rasmus Ischebeck)

Sliced Emittance Measurements at the SwissFEL Injector Test Facility

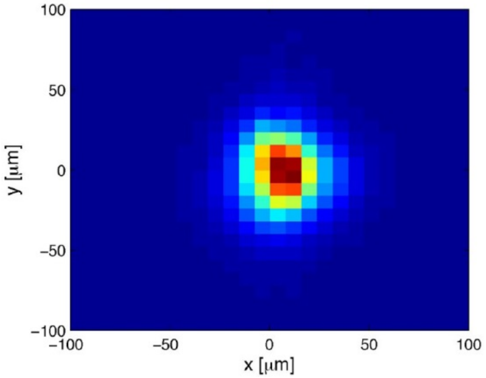
SITF measurements performed by: Marta Divall & Eduard Prat



core sliced ε as a function of charge



SwissFEL SCM resolution test with 10 pC



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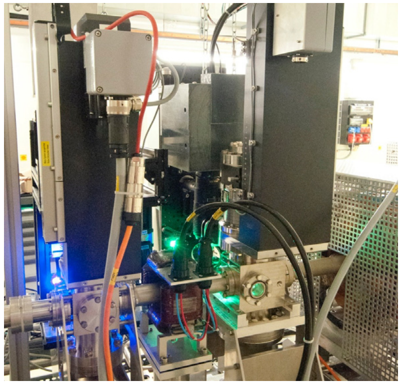

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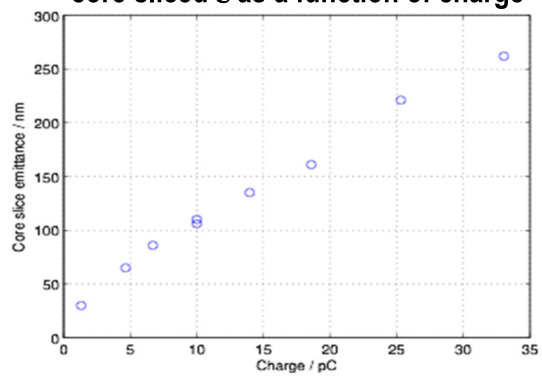

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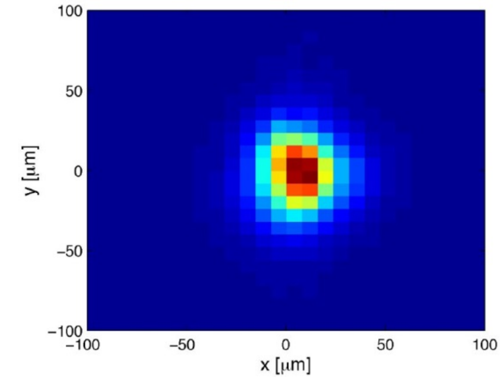
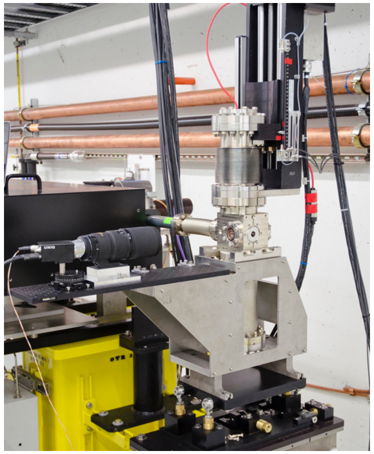
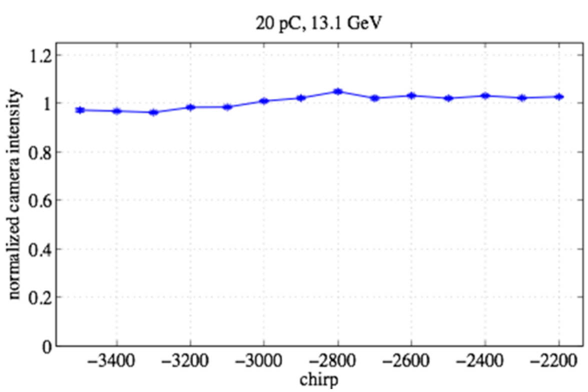


Measurements at the LCLS linac-to-undulator Line

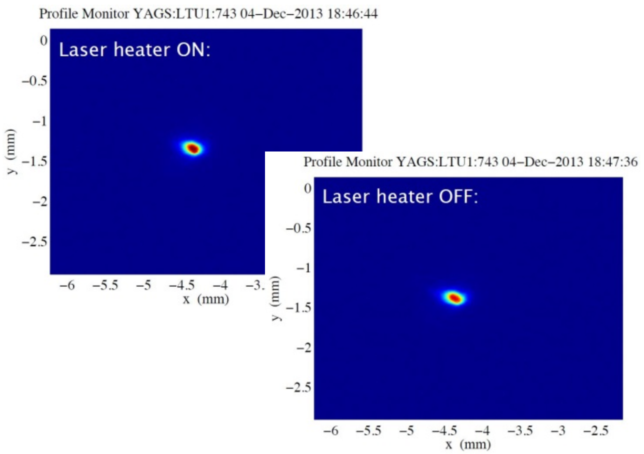
LCLS measurements performed by: Patrick Krejcik, Henrik Loos (LCLS) & Minjie Yan (DESY)



intensity as a function of compression
(not effected by COTR or saturation)



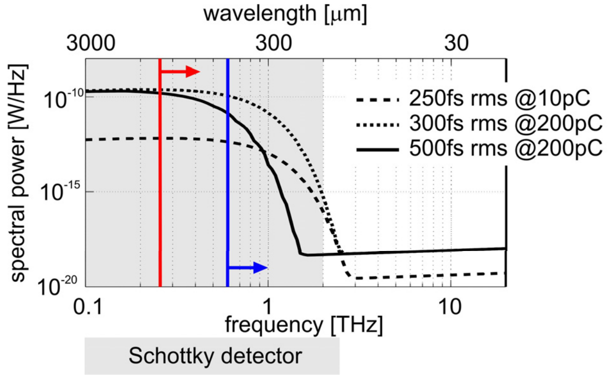
COTR suppression tests at LCLS (full compression, 20 pC)

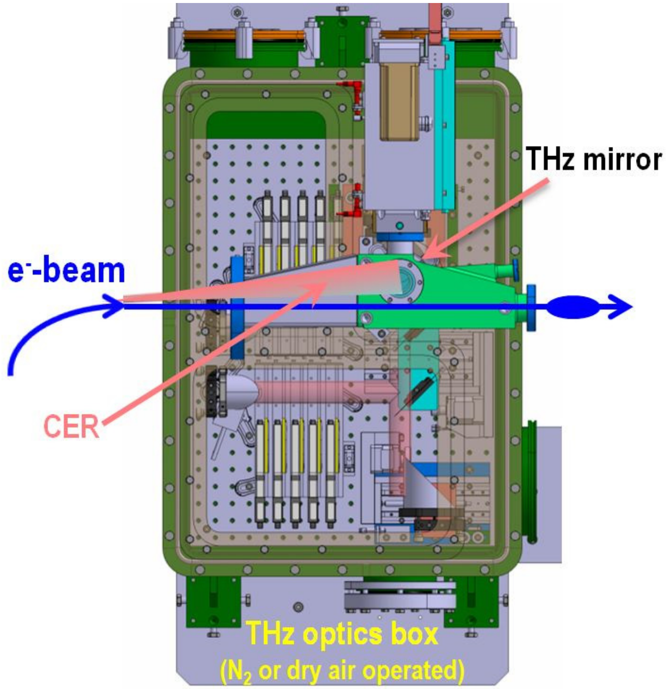


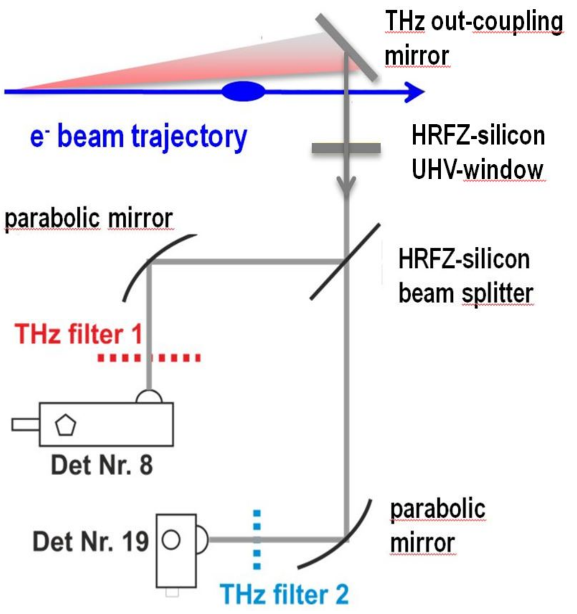
SwissFEL BC-1 THz Compression Monitor (design by Franziska Frei & Dani Treyer)

- use of coherent edge radiation from 4th BC-1 diplole (non-invasive)
- two signal paths for observation of different spectral (THz-) ranges for sensitivity to different bunch lengths
- use of THz high pass filters and broadband Schottky diodes
- ND-filters for intensity adjustment (bunch charge range: 10 – 200 pC)
- read-out electronics similar to button-type BPM RF front end

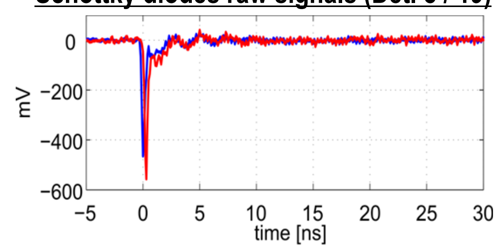
spectral range of CER and THz filters for BC-1





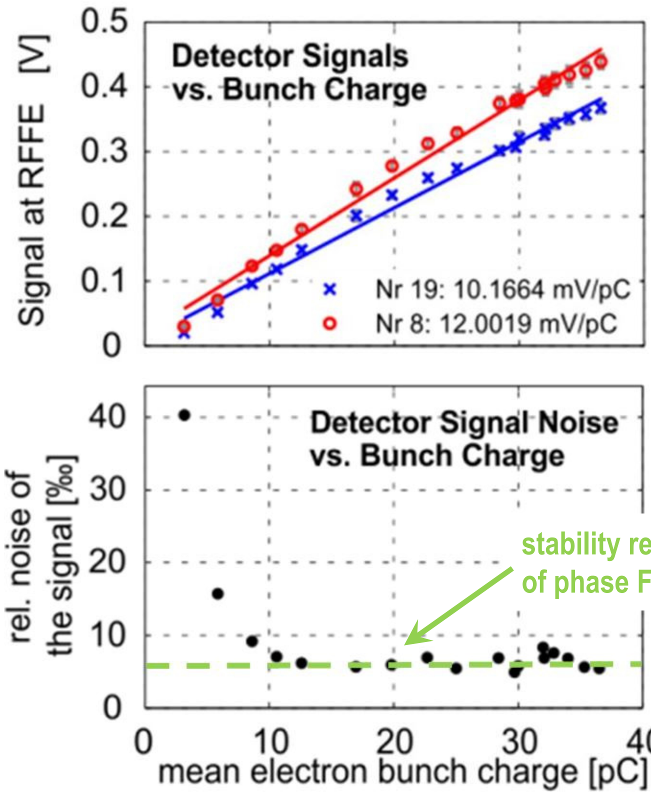


Schottky diodes raw signals (Det. 8 / 19)



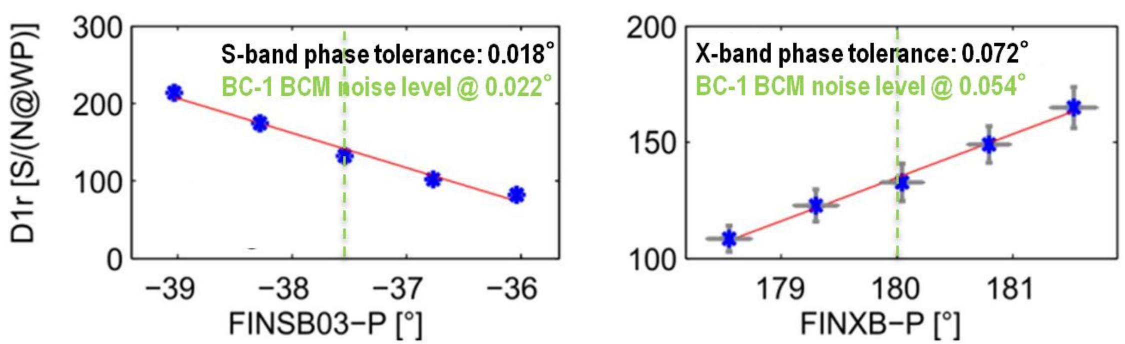
SwissFEL BC-1 THz Compression Monitor (design by Franziska Frei & Dani Treyer)

- quasi-linear behaviour of Schottky diode signals within the nominal operation range of BC-1 compression monitor (10 – 200 pC)
- SwissFEL operation modes with 2-bunches (@ 28 ns bunch distance) and low charge (10 pC) are feasible with Schottky diodes



S- and X-band Phase Scans at SITF for nominal compression

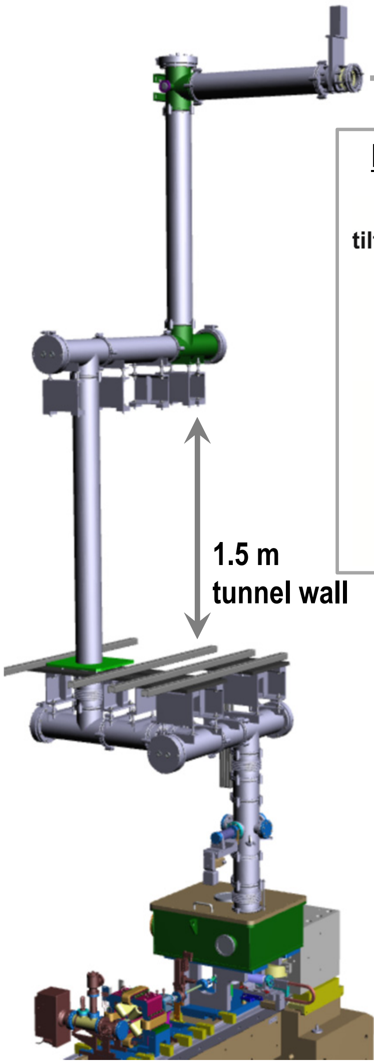
(Schottky detector #19 with 0.6 THz high pass filter)

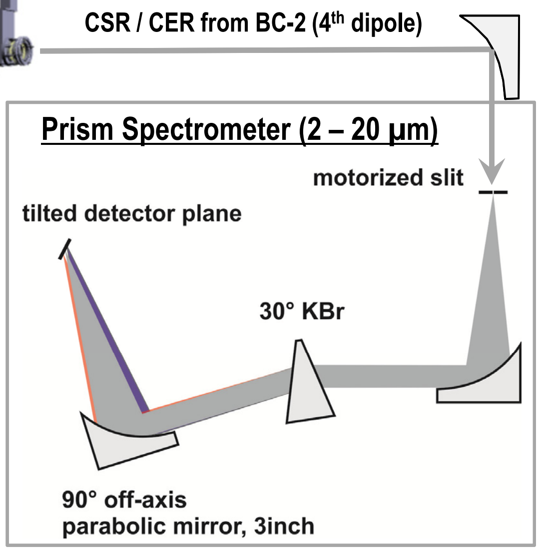


→ S/N of BC-1 compression monitor is sufficient for RF phase feedback around S- and X-band working points

SwissFEL BC-2 Compression Monitor (presently under design by Franziska Frei)

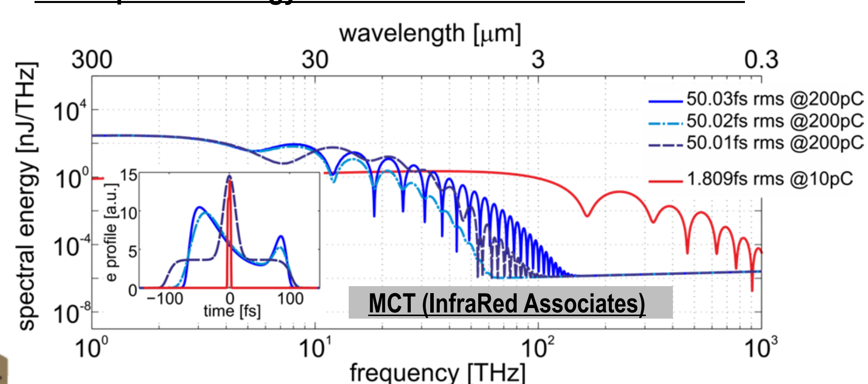
BC-2 BCM Optical Transfer Line



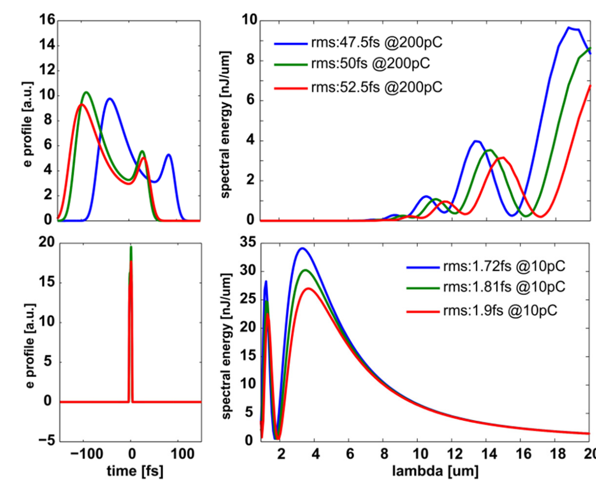


- use of coherent edge or synchrotron radiation for completely non-invasive set-up
- evacuated optical transfer line from LINAC tunnel to technical gallery
- prism spectrometer (KBr) using a MCT detector array operated in dry air environment

CSR Spectral Energy Distribution for SwissFEL Bunches



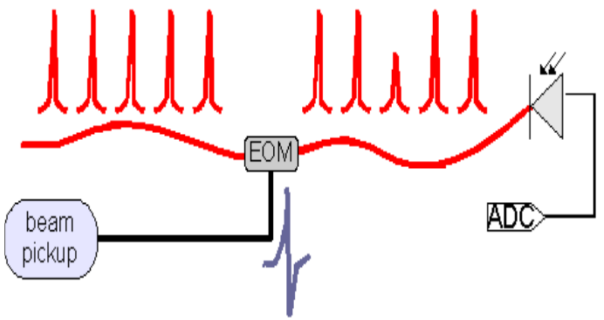
CSR for SwissFEL «long» & «short» Bunch Modes



SwissFEL EO Bunch Arrival Time Monitor (design by Vladimir Arsov)

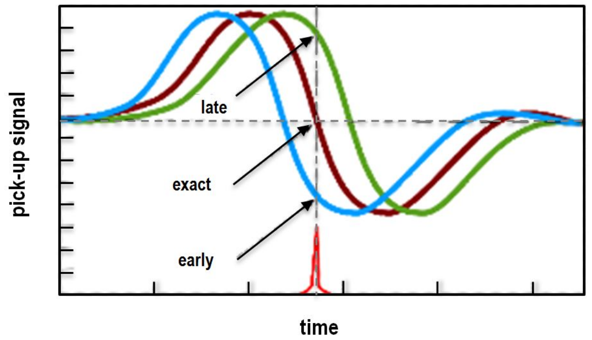
EO BAM Principle

Correlation of beam signal from a high-bandwidth pick-up with laser pulses from the highly stable optical reference system (sub-10 fs jitter and drift) in an EO modulator



EO BAM Components for SwissFEL

- use of high bandwidth (40 GHz) and low IL components *:
  → pick-up & UHV feedthroughs, EOMs, RF cables...
- improved BAM pick-up support for micrometer adjustment and well defined (shortest) RF cable routing
- improvements in BAM Front End Box and DAQ system



EO BAM Performance for SwissFEL

- 7 – 13 fs resolution in the charge range from 30 – 200 pC (12bit ADC / 16 mm PU diameter)
- < 10 fs expected for SwissFEL at 10 – 200 pC (16bit ADC / 8 mm PU diameter)
- 4 EO BAMs will be installed for SwissFEL phase-1

* in collaboration with DESY and TU-Darmstadt / see: A. Angelovski et. al, Phys. Rev. ST Accel. and Beams, 15, 112803 (2012)

SwissFEL EO Laser Arrival Time Monitor (EO BAM adaptation by Albert Romann)

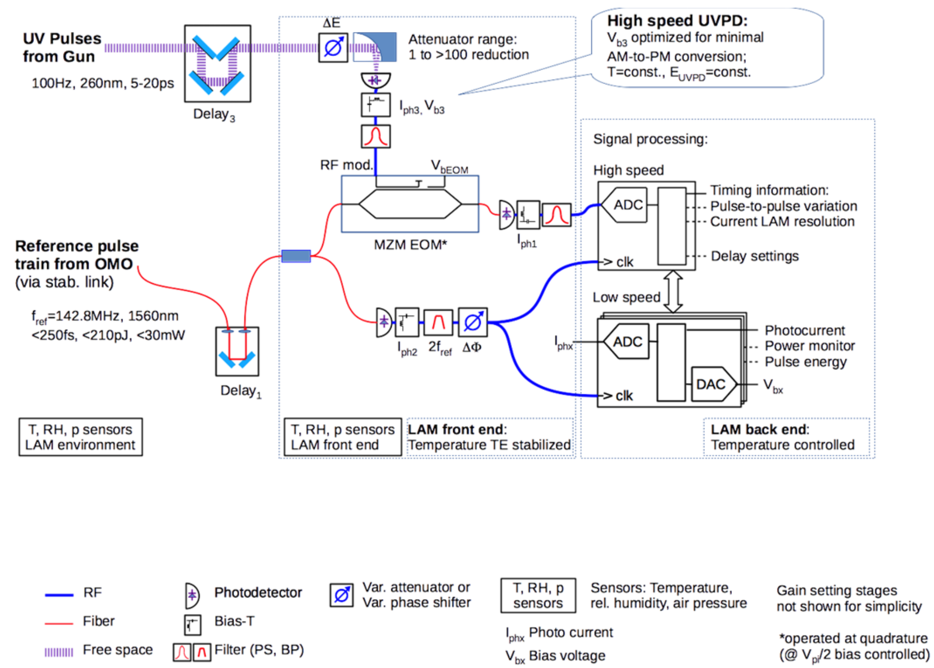
- For SwissFEL laser arrival time will be measured at the gun (UV-pulses) and at the experimental stations

- Gun LAM adapts EO BAM scheme…:
  - → high speed UV photo diode (optimized for minimal AM/PM conversion) instead of beam pick-up
  - → most EO front end components are similar to EO BAM
  - → most of the DAQ-system is similar to EO BAM

- EO LAM provides large measurement range (tens of ps) with high resolution (order of 10 fs) compared to (spectrally resolved) auto- or cross-correlators applied at experimental stations (sub-ps range with few fs resolution)

- **Status:** components have been tested
  demonstrator expected by end of 2015
  prototype Q2 2016 ready for SwissFEL injector commissioning

Schematics of SwissFEL EO LAM



Status, Conclusions & Outlook

→ SwissFEL Diagnostics is ready for ARAMIS commissioning

→ most monitors have been successfully tested at SITF, FLASH, FERMI and LCLS

→ all monitors and fulfill SwissFEL requirements and will be feedback-ready

→ integration in new SwissFEL control system is still ongoing

→ ARAMIS photon diagnostics will be ready to support SwissFEL commissioning

→ S-band (injector) and C-band TDS will be available for commissioning

→ further longitudinal diagnostics for shortest bunches is still under development

→ new ideas are under consideration:

THz streak camera for hard X-rays
(P. Juranic et al., Opt. Express 2014 Dec 1; 22 (24):30004-12)

THz-streaking for electrons
(M. Dehler et al., this conference proc.: MOPB048)

plasma “peak current” monitor
(R. Tarkeshian et al., this conference proc.: MOPB052)

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many thanks to…:

→ **the SwissFEL team, beam dynamics, controls and operation**

→ **all PSI support and infrastructure groups**

→ **many external collaborators (DESY, SLAC, FERMI, KIT, Uni Bern…)**

→ **all members of the PSI Diagnostics Section** (working for SwissFEL)

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