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Commissioning Experience and First Results of SwissFEL Diagnostics

DEELS 2017 @ SOLEIL, Give-sure-Yvette, France

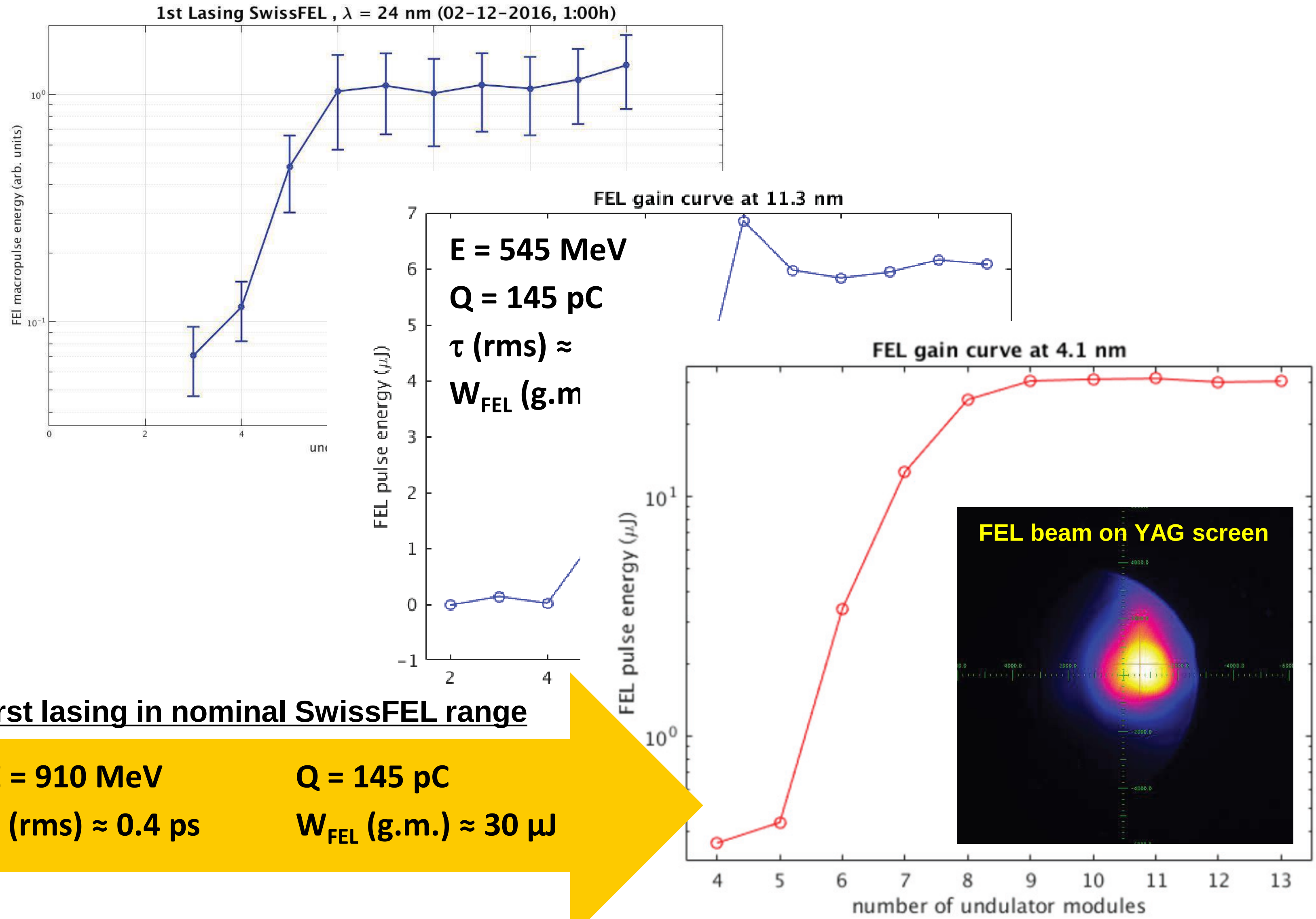
Outline…

- **Status of the SwissFEL Project**
- **Overview of SwissFEL Diagnostics**
- **First Commissioning Experience with…:**
  - **BPMs**
  - **Screen Monitors and Wire Scanners**
  - **BC-1 Synchrotron Radiation Monitor**
  - **Charge and Loss Monitors**
  - **BC-1 Compression Monitor**
- **Summary and Outlook**

Status of the SwissFEL Project - Milestones

- **February 2015:** **access to SwissFEL building for installation**
- **August 2016:** **first electrons from photo-injector gun (7.9 MeV)**
- **September 2016:** **LINAC and transfer line installation completed**
  first electrons accelerated with C-band modules towards injector beam dump
- **October 2016:** **undulator lines up to main beam dump completed and under vacuum**
- **November 2016:** **first beam transport through undulators**
- **December 2016:** **first lasing (345 MeV, 24 nm) and inauguration**
- **May 2017:** **first lasing at 11.3 nm and 4.1 nm**

Status of the SwissFEL Project - Achievements



first lasing in nominal SwissFEL range

E = 910 MeV **Q = 145 pC**

τ (rms) ≈ 0.4 ps **W_{FEL} (g.m.) ≈ 30 μJ**

SwissFEL Diagnostics - Requirements

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

→ high BW 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

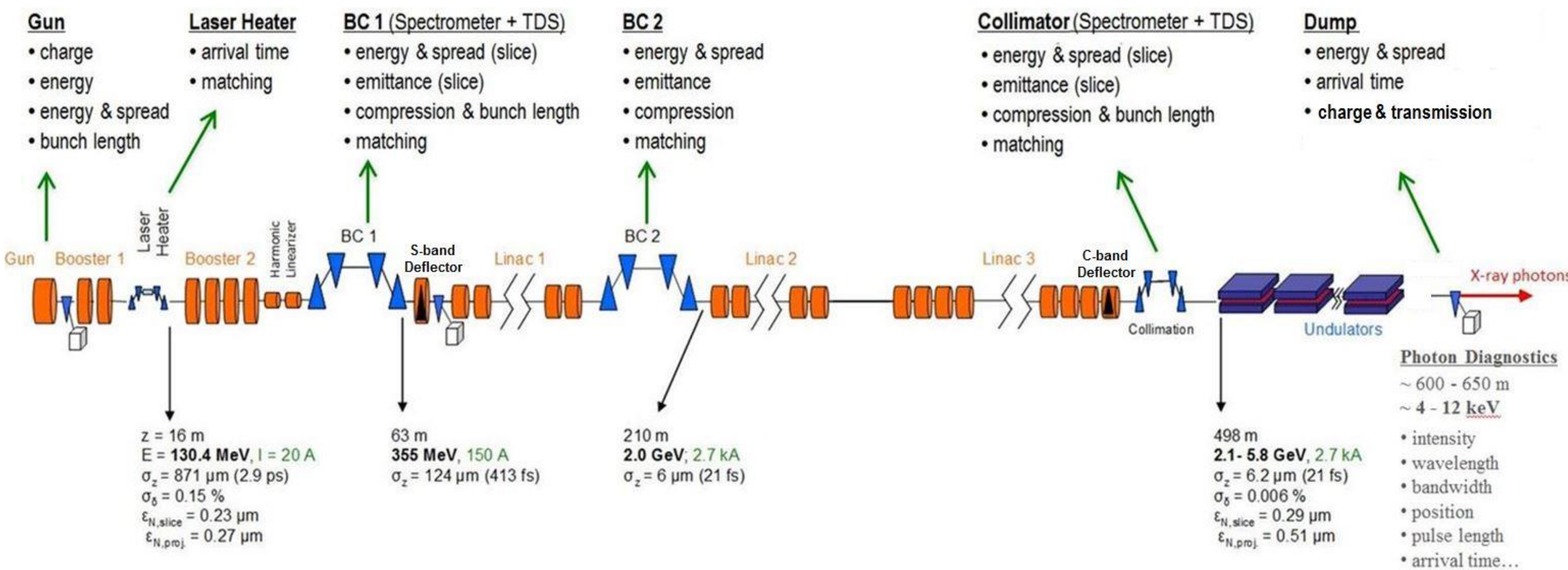
SwissFEL Diagnostics - Overview

→ **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 and non-invasive longitudinal diagnostics monitors behind BC-1 and ARAMIS collimator**

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



SwissFEL Diagnostics - Systems (ARAMIS)

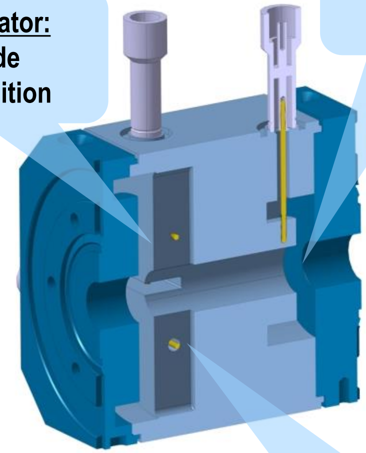
Beam Position Monitors:	7 x BPM-38 / 111 x BPM-16 / 27 x BPM-8 (all cavity-type BPMs)
Screen Monitors:	10 x high sensitivity, high resolution SCM for meas. at 100 Hz 14 x SCM for observation and control room support at 10 Hz
Wire Scanners:	23 x WSC along LINACs, TLs and ARAMIS undulator
Synchrotron Radiation 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)

Commissioning Experience - BPMs

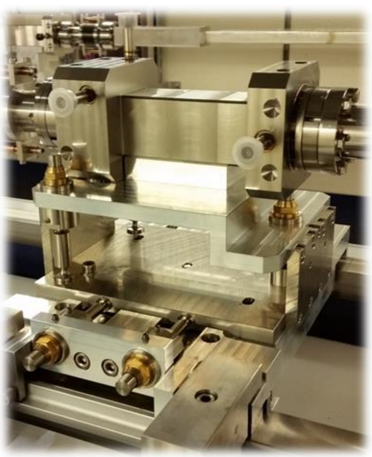
	CBPM38	CBPM16	CBPM8
Aperture [mm]	38	16	8
Length [mm]	255	100	100
Material	Steel 316LN	Steel 316LN	Steel 316LN + Cu Core
Frequency [GHz]	3.2844	3.2844	4.9266
Q_L	38	38	1000
Bunch Spacing	28ns	28ns	10ms
Position Signal [V/mm/nC]	5.7*	7.1*	4.3*
Charge Signal [V/nC]	66*	135	58

* value for one PU-port while 2nd is terminated with 50 Ω.
Combination of two PU-ports increases signal by ~ sqrt(2) (done for the position signals of all BPMs)

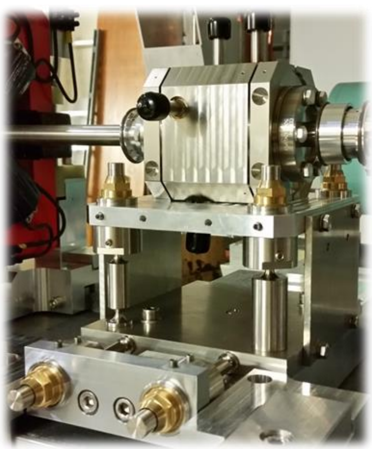
CBPM16 Pickup



CBPM38 Pickup

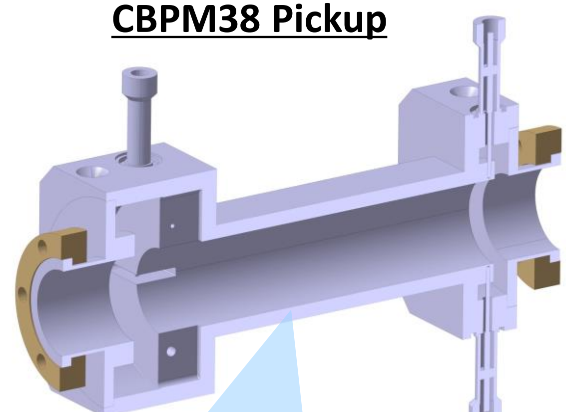


CBPM16 Pickup



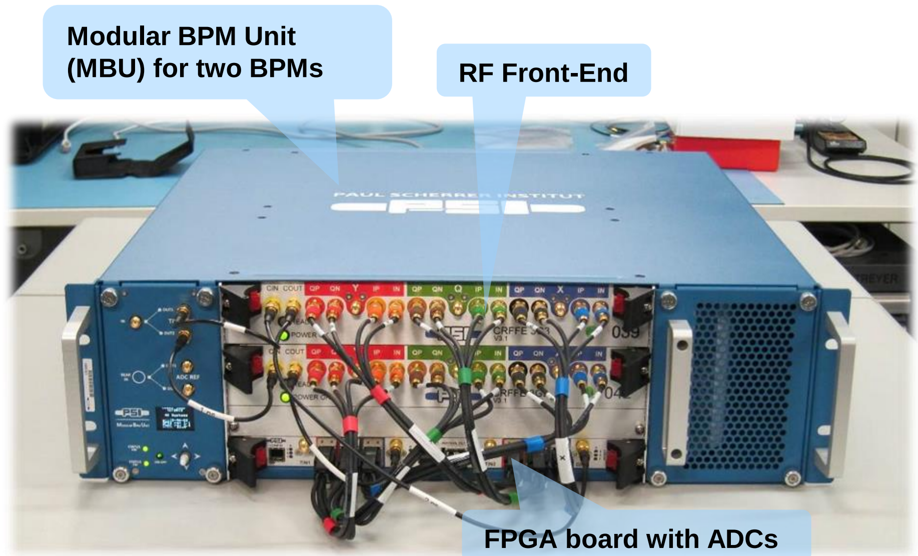
CBPM8 Pickup

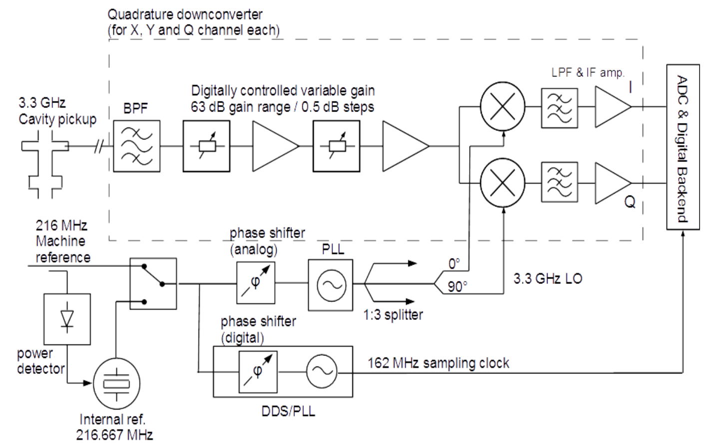
CBPM38 Pickup



Commissioning Experience - BPMs

SwissFEL Cavity BPM Electronics

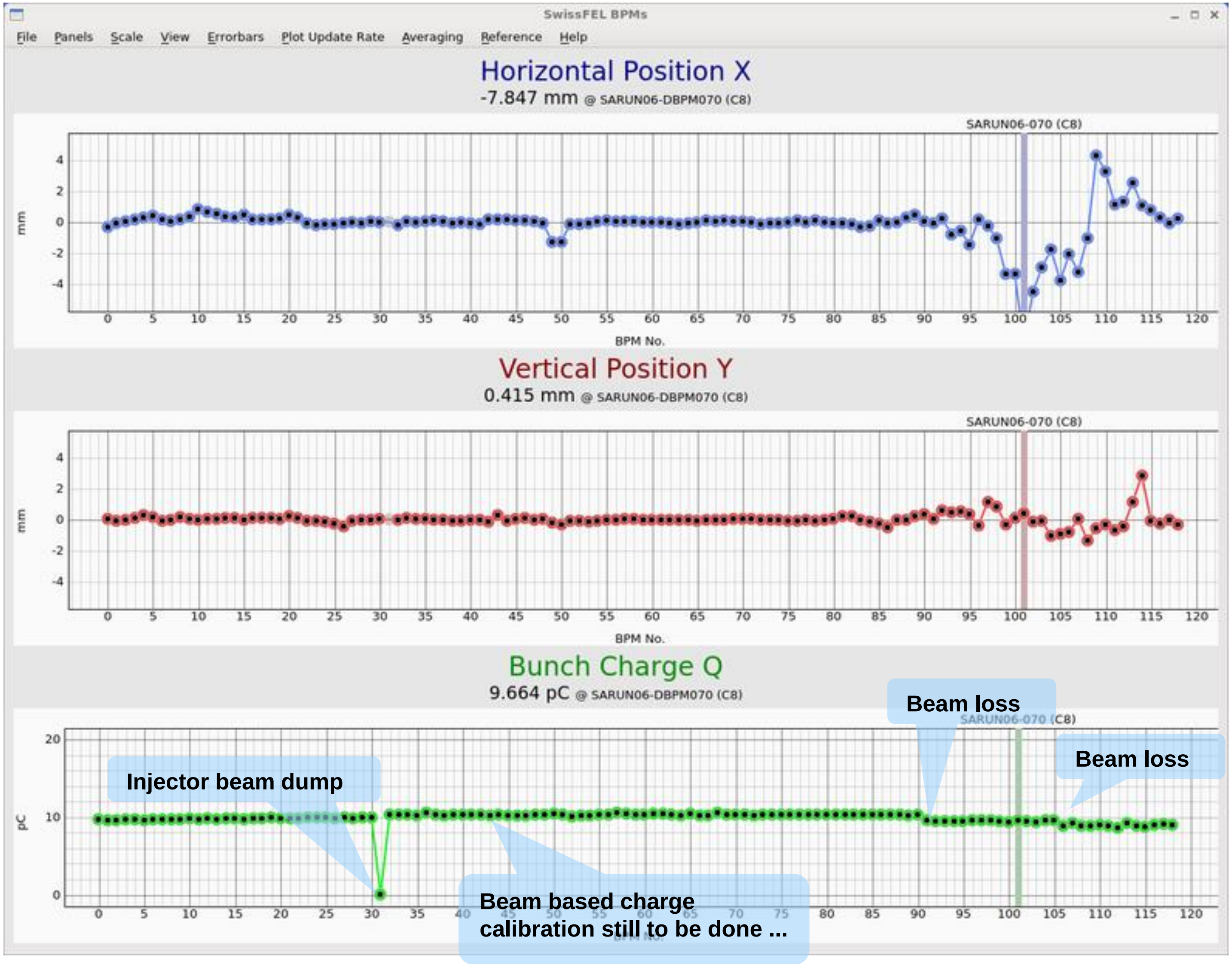




Present BPM Usage in SwissFEL

- **119 cavity-type BPMs in operation**
- **alignment of beam trajectory (minimize wakes in RF structures, e-beam / x-ray overlap)**
- **energy measurement in BC arms & dump spectrometers**
- **charge and transmission / loss measurement and coarse arrival time monitoring**
- **correction of position & charge dependency of other diagnostics (BCMs, wire scanners)**

Commissioning Experience - BPM GUI



BPM Performance (preliminary)

Single Bunch Position Resolution for All BPM Types:

< 1 µm RMS @ 10 pC (range ± 0.5mm)

< 0.5 µm RMS @ 20 pC (range ± 0.5mm)

CBPM8 (high-Q) better than low-Q, still optimizing FPGA algorithm ...

Single Bunch Charge Resolution:

CBPM38/16:

< 0.07 % RMS (relative) for larger bunch charge

< 4 fC RMS for very low bunch charge

CBPM8:

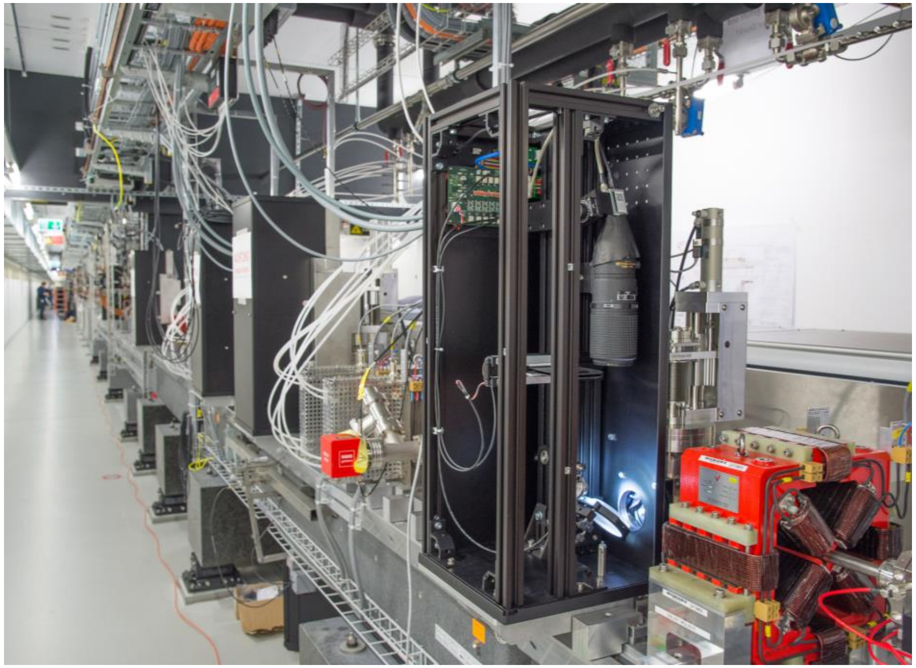
< 0.04% RMS (relative) for larger bunch charge

< 3 fC RMS for very low bunch charge

Comment: Resolution at low charge depends on pickup RF cable length (CBPM38/16: typ. some 10m length, CBPM8: typ. <10m length, using ½" Succofeed + short low-loss patch cables)

Commissioning Experience - Screen Monitors

View of Screen SwissFEL Monitor Stations



Screen Monitor Design Criteria

→ **design of optical path avoids COTR blurring**

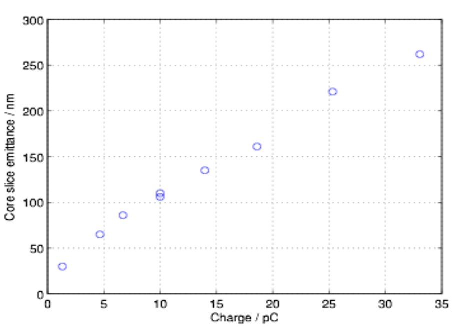
→ **scintillators: LuAG and YAG crystals**

→ **observation acc. to Snell's law of refraction allows imaging of beams < scintil. thickness**

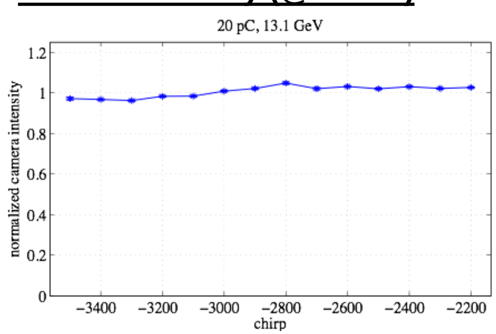
→ **large ROI without depth of field issue**

→ **tilted CMOS sensor avoids astigmatism**

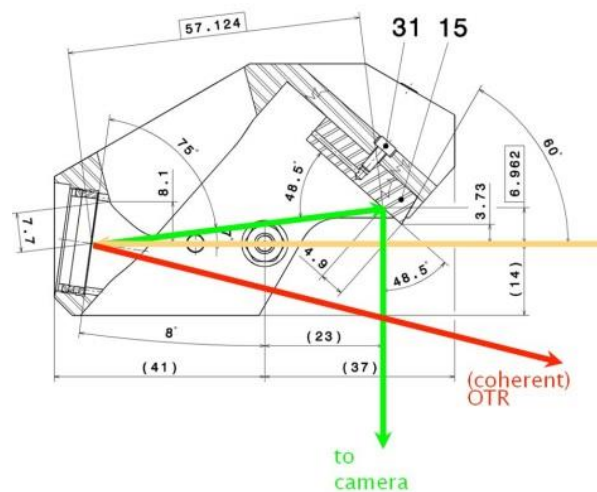
SITF Slice ε-Measurements



COTR Immunity (@ LCLS)



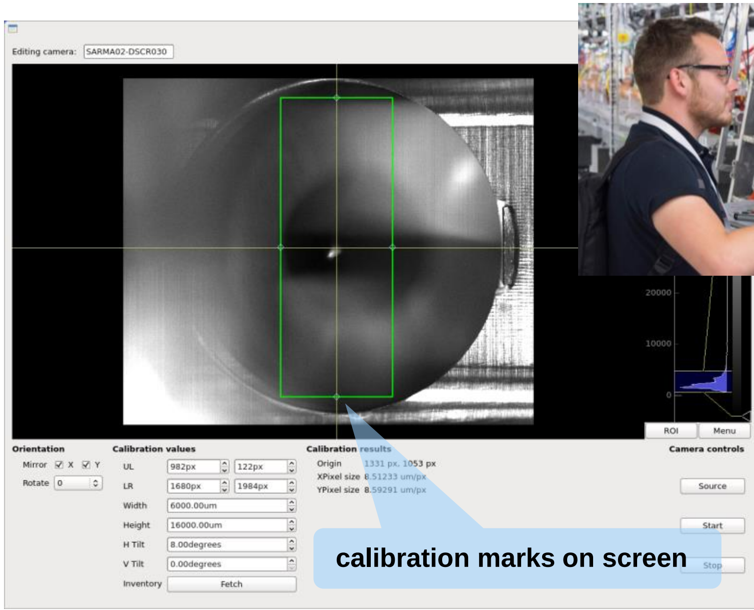
Screen Monitor Optical Path



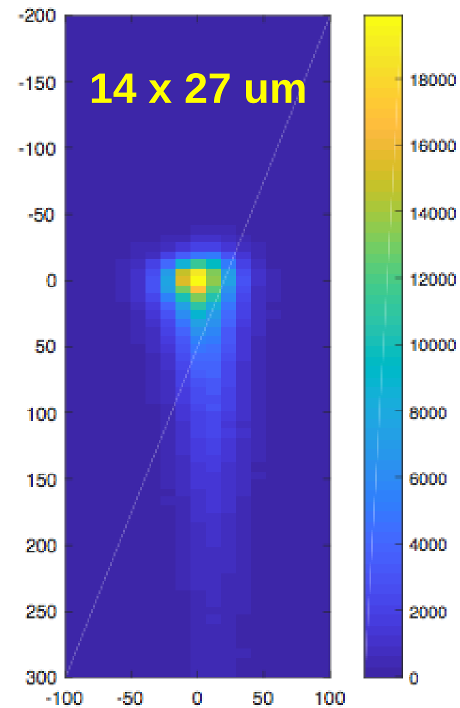
European Patent EP 2 700 979 A1

Commissioning Experience - Screen Monitors

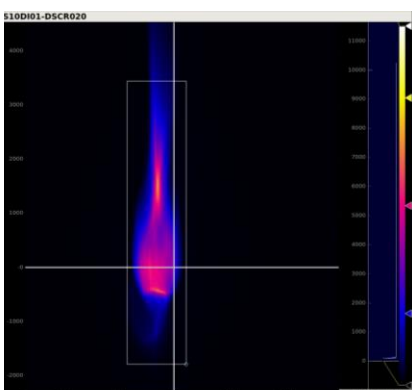
Screen Monitor Alignment & Calibration



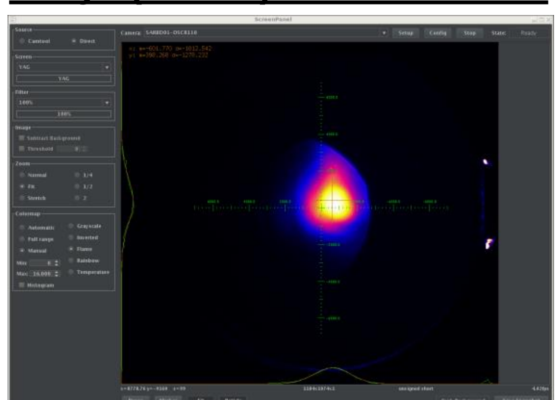
small electron beam size



streaked electron beam

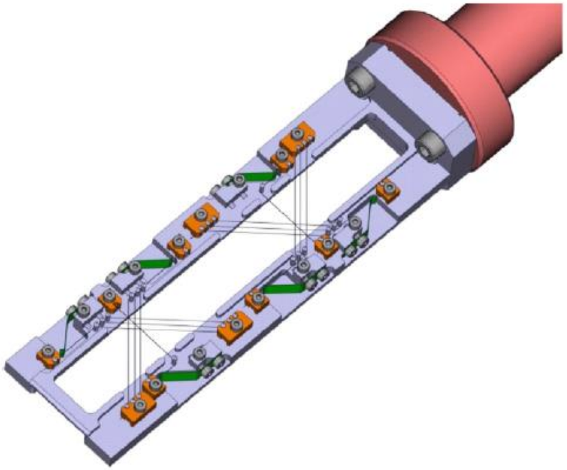


x-rays (4.1 nm) from undulator



Commissioning Experience - Wire Scanners

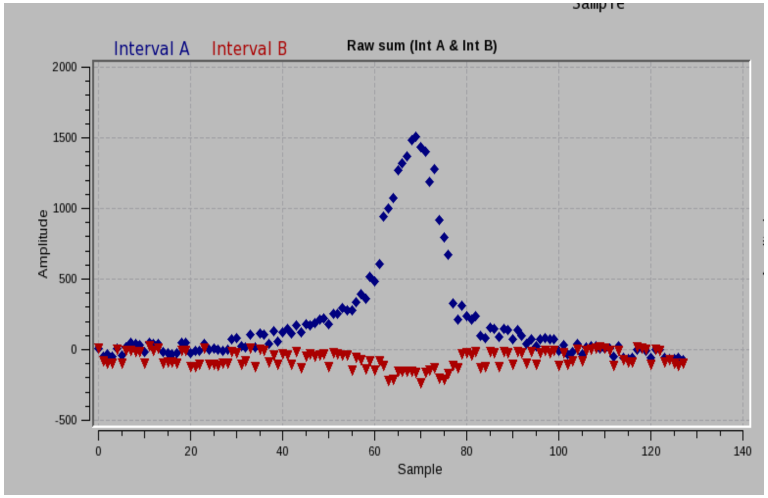
SwissFEL Wire Scanner Fork



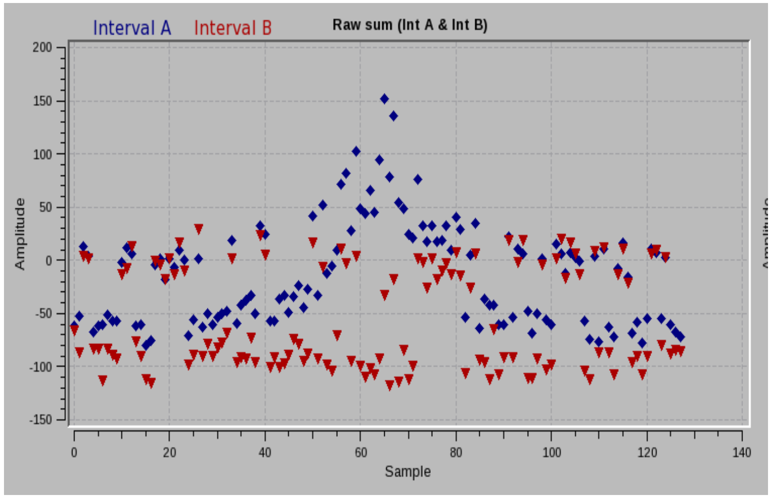
- WSC-fork equipped with 5 μm Tungsten and 12.5 μm Al(99):Si(1) wires (3 possible pin-slots for positioning X and Y wires)
- Beam loss ratio between Tungsten and Al(99):Si(1) wires: ~ 10 / 1
- wire vibration determined within stability limit of ≤ 1.3 μm rms (at Delta-Tau 2 –phase stepper motor speed of 0.1 - 3.0 mm/s)
- 15 (out of 22) WSCs presently installed in SwissFEL
- beam-synchronous acquisition of the encoder reading (jitter ~0.1ms) and beam-loss-monitor read-out

Examples of SwissFEL beam profile measurement taken at 148 MeV, 10 pC and 10 Hz…:

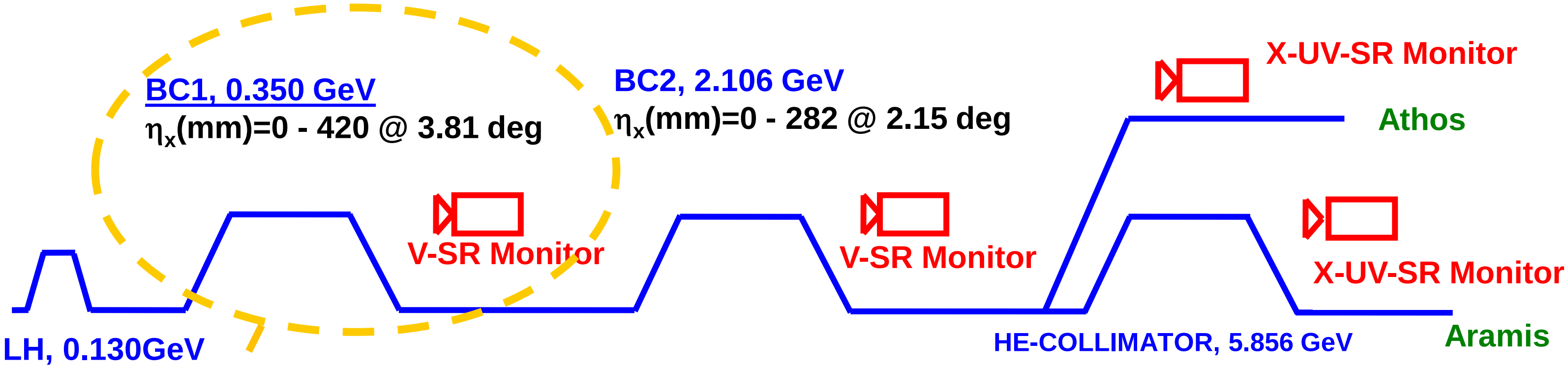
5 μm tungsten wire



12.5 μm Al(99):Si(1) wire



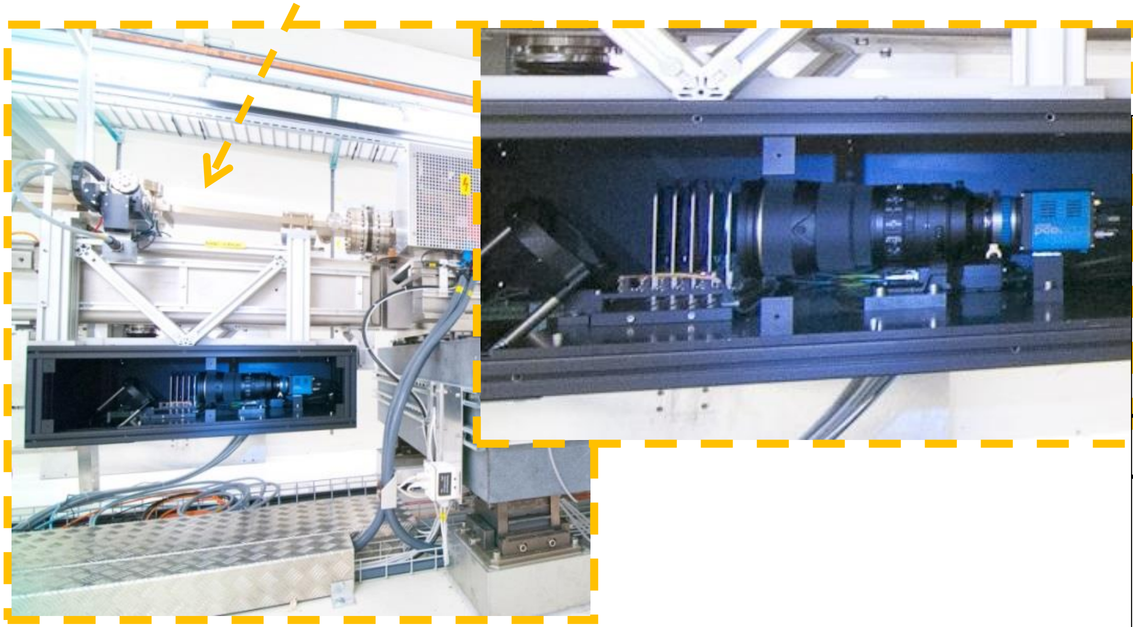
SwissFEL SR Monitors for Bunch Compressors



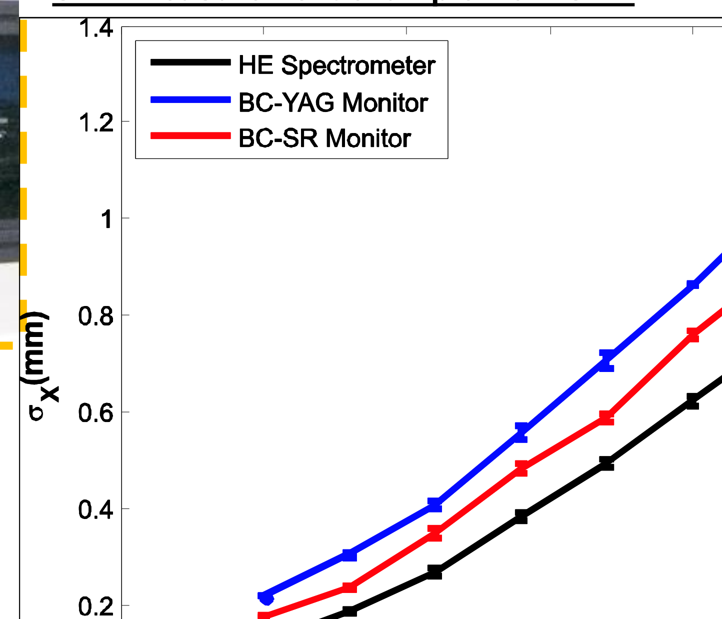
Gun:
σ_z(10 pC, rms) = 334 μm
σ_z(200 pC, rms) = 871 μm

BC1:
σ_z(10 pC, rms) = 66.8 μm (C.F.=5)
σ_z(200 pC, rms) = 87.1 μm (C.F.=10)

BC2:
σ_z(10 pC, rms) = 1.0 μm (C.F.=300)
σ_z(200 pC, rms) = 5.7 μm(C.F.=150)



SRM measurement example from SITF

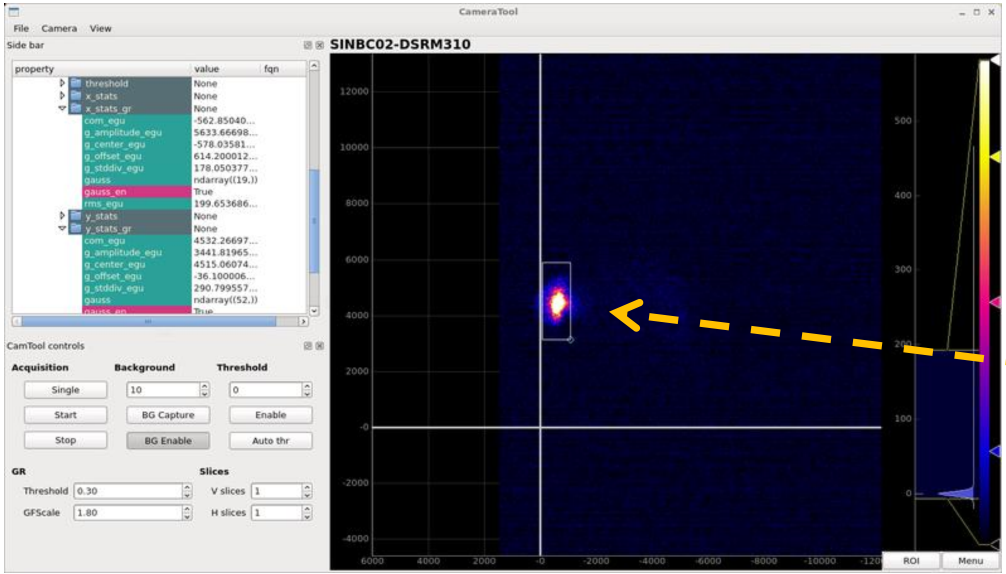


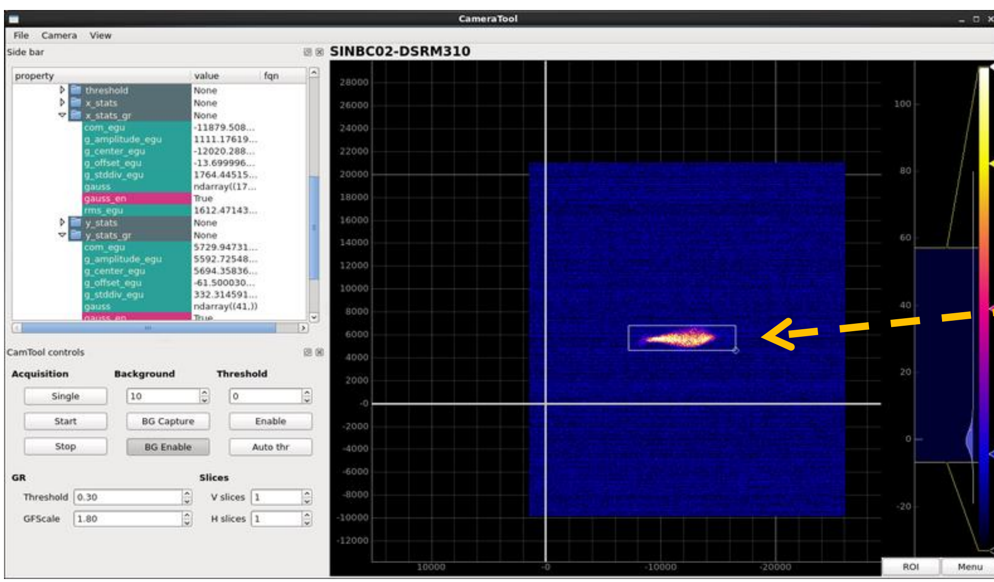
BC-1 and BC-2 SR Monitor Specifications

	SwissFEL Specification BC-1 SRM	SwissFEL Specifications BC-2 SRM
Dynamic Range	10 to 200 pC	10 to 200 pC
Detector: sCMOS camera (100fps) (Field of View=68mm, in-vacuum mirror)	Optical Fiber Camera Link, standard lens (Nikon 300mm), further upgrade to a 2-bunches (28ns) camera system	Optical Fiber Camera Link, standard lens (Nikon 300mm), further upgrade to a 2-bunches (28ns) camera system
Relative Energy Spread Resolution	1.2*10^-4 (BC1, 350 MeV)	1.7*10^-4 (BC2, 2.1 GeV)
Beam Size at 3rd dipole (max OFF-crest phase of RF)	6.0 mm (BC1,rms)	1.2 mm (BC2,rms)
Repetition Rate/image-Processing-Rate	100 Hz/100 Hz	10 Hz/100 Hz
Up-Grade to 2-Bunch Operations (28 ns)	Camera-box ready for the upgrade to a 2-bunches camera system	
Machine Feed-Back (Real-Time)	1st,2nd,3rd momenta vs. RF parameters (S-Band chirping and X-band linearizing)	

- **BC-1 and BC-2 SRMs will use visible light from 3rd BC bending magnet (location of maximum dispersion)**
- **simulations predict that coherent SR due to micro-bunching should not disturb (glare) measurements in BC-1 or BC-2 if Laser-Heater is on**
- **BC-1 and BC-2 SRMs are installed and operational**
- **UV (X-ray) SRMs for ATHOS dog-leg and HE ARAMIS-collimator are still under design**

First Measurements from BC-1 Commissioning





<u>SwissFEL Beam Conditions</u>

- **Energy: 150 MeV**
- **Charge: 12 pC**

<u>SR light from "on-crest beam spot"</u>

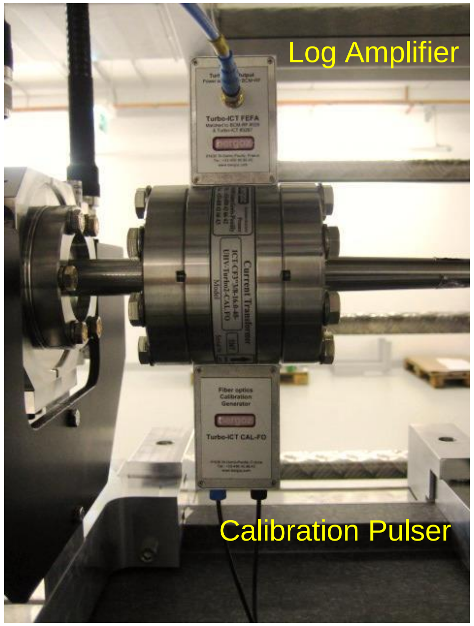
- **σ_x (rms): 180 μm**
- **σ_y (rms): 200 μm**
- **ΔE/E ~ 75 keV**
  (estimated for nominal BC-1 dispersion of 400 mm but not yet confirmed by meas.)

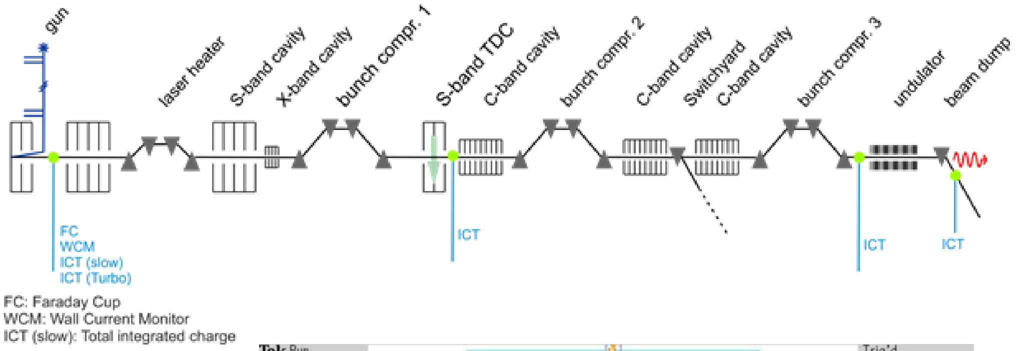
<u>SR light from "off-crest beam spot"</u>

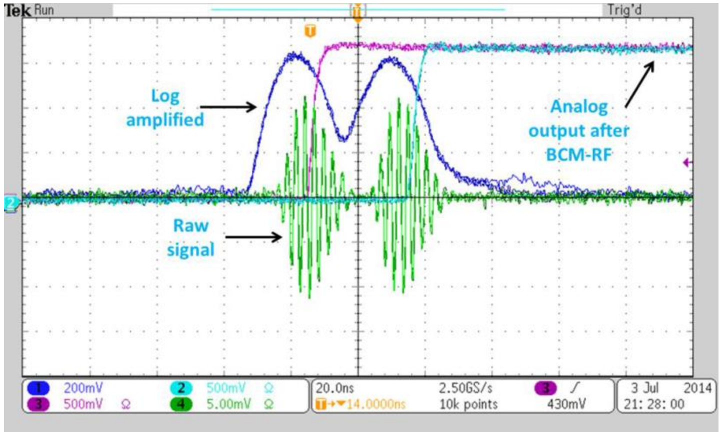
- **σ_x (rms): 1600 μm**
- **σ_x (Gauss): 1750 μm**
- **ΔE/E ~ 700 keV**
  (estimated for nominal BC-1 dispersion of 400 mm but not yet confirmed by meas.)

Beam Charge Monitors – Turbo ICTs / BCM-RF

- **all 4 Turbo-ICTs with BCM-RF electronics are installed and operational**
- **absolute charge readings from different ICTs differ between 4 – 6 % (4 % was absolute calibration limit)**
- **further investigations are required to match pre-calibration in lab and the beam measurement**
- **ICTs are integrated in SwissFEL Machine Protection System and used for charge calibration of BPMs**







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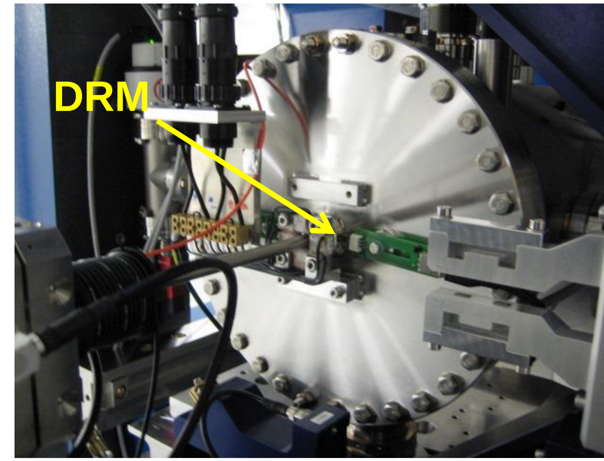
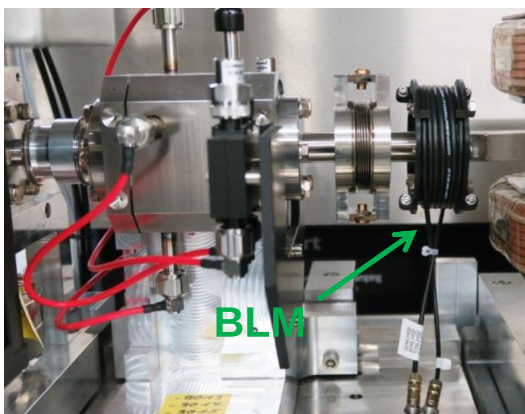
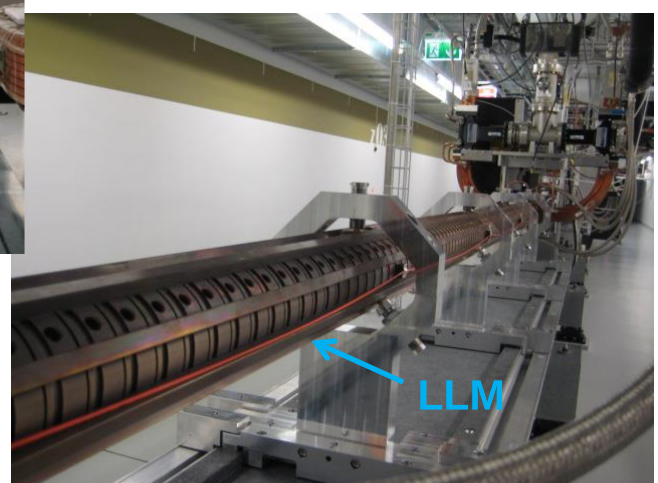
Commissioning Experience – Loss Monitors

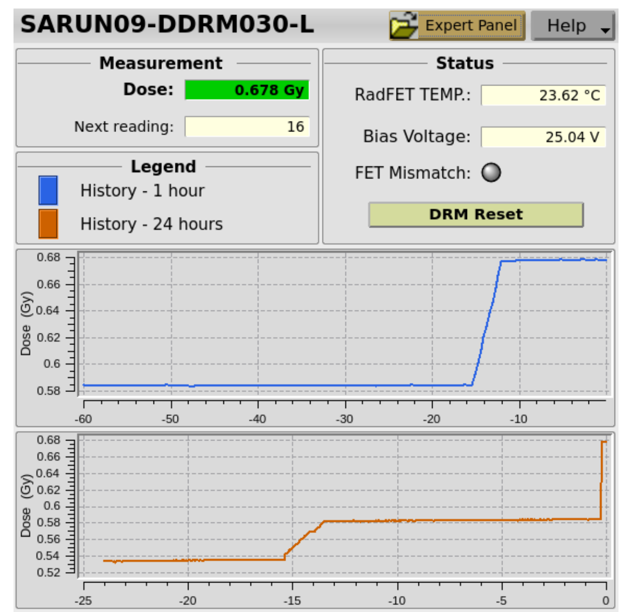
Beam Loss Monitors - Cerenkov Fibers and Dose Rate Monitors

- **all BLMs, LLMs and DRMs are installed and operational**
- **beam loss thresholds have been determined to keep SwissFEL operation "safe" (below DRPS limits)**
- **BLMs are triggering the SwissFEL Machine Protection System for adjustment of rep-rate in case of losses**
- **Dose Rate Monitors (commercial devices) are installed and operational for ARAMIS undulator protection**





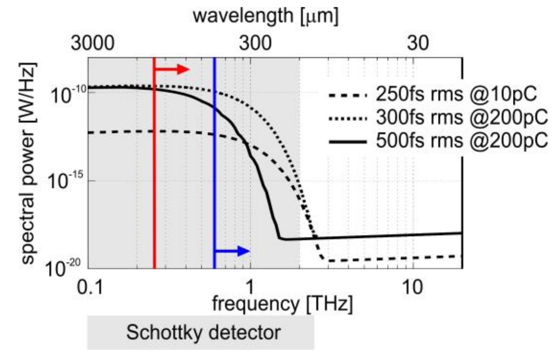


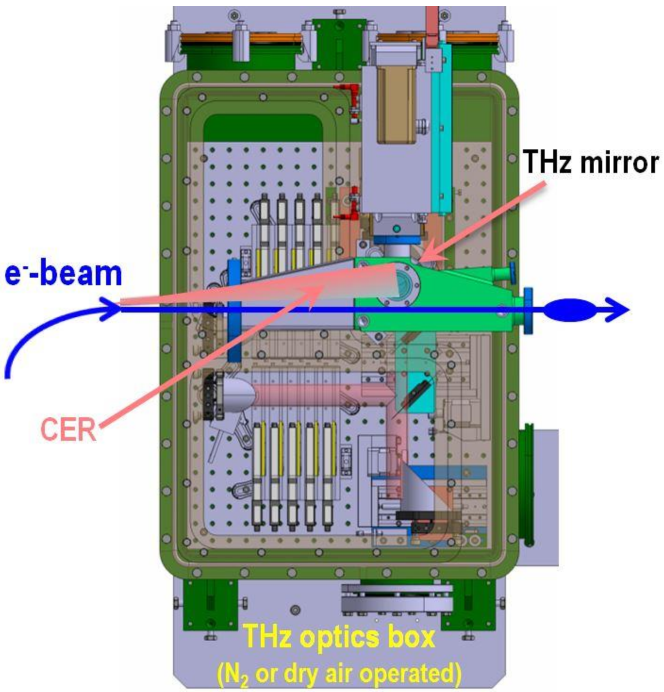


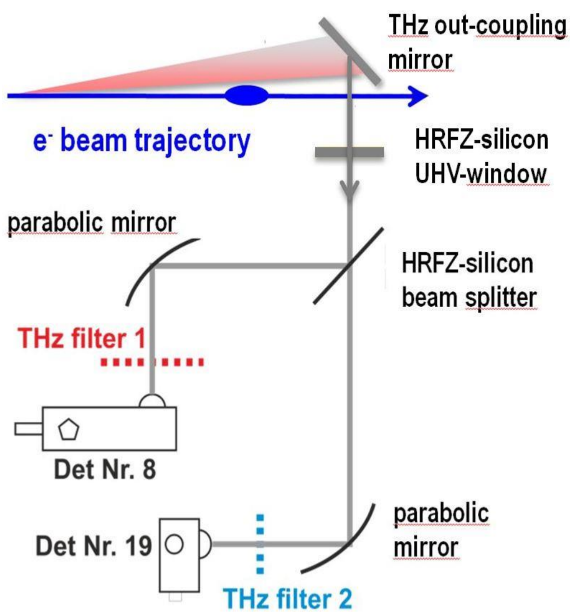
BC-1 Compression Monitor

- 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

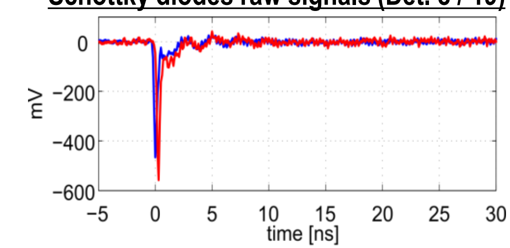
spectral range of CER and THz filters for BC-1







Schottky diodes raw signals (Det. 8 / 19)



First Signals from BC-1 Compression Monitor

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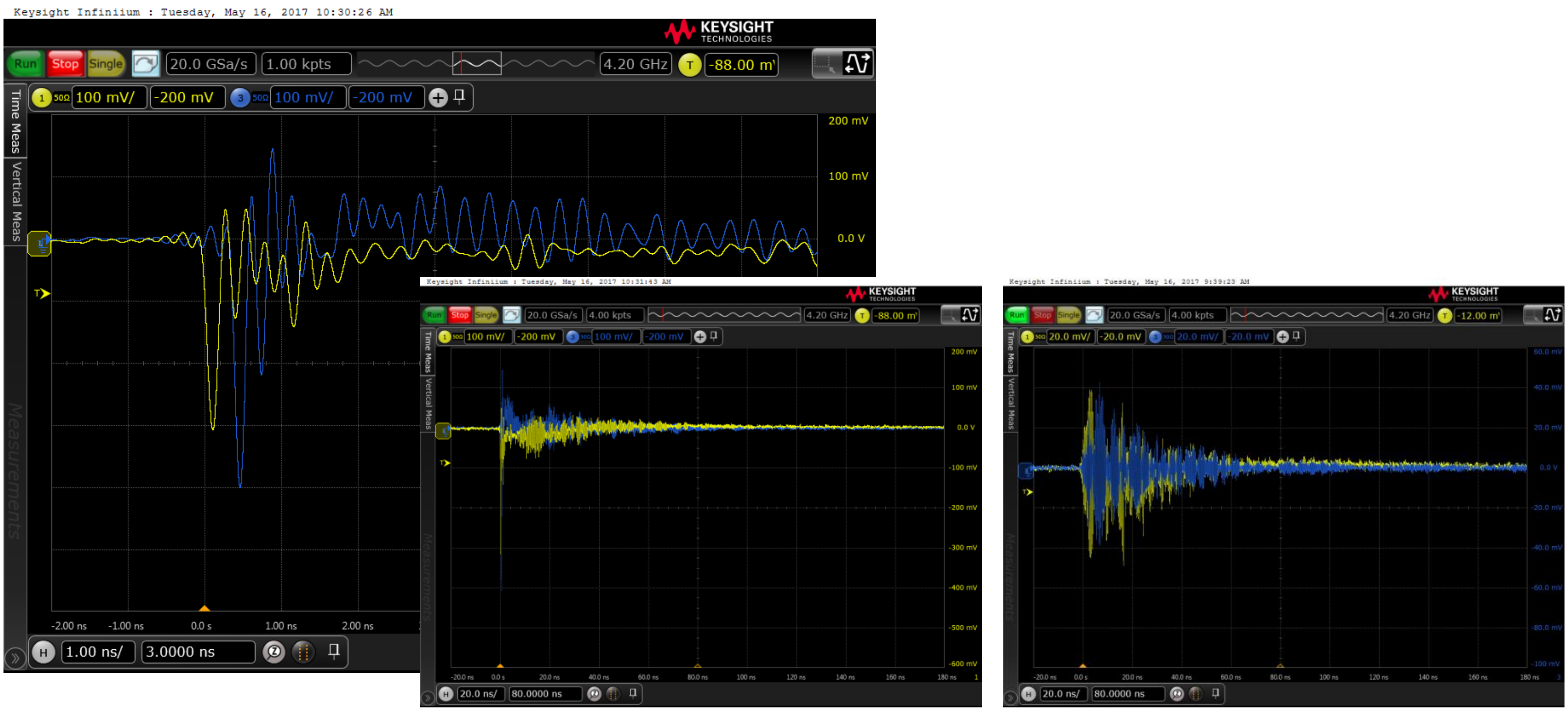
BC-1 Compression Monitor - Shottky Diodes with Spectral Filtering (THz-Range)

- **first signals from BC-1 compression monitor have been seen on both Shottky diodes (with THz filters)**
- **sufficient CSR-signal for beam of E = 330 MeV, Q = 120 pC and τ = 460 fs (rms)**
- **Shottky diode signals are still “contaminated” with long ringing (wakefields or reflections?)**
- **dependency of signal intensity on off-crest S-band and X-band phase settings could already be observed**



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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…)**

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