Advanced Beam Diagnostics Tools for the SwissFEL Project

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Outlook

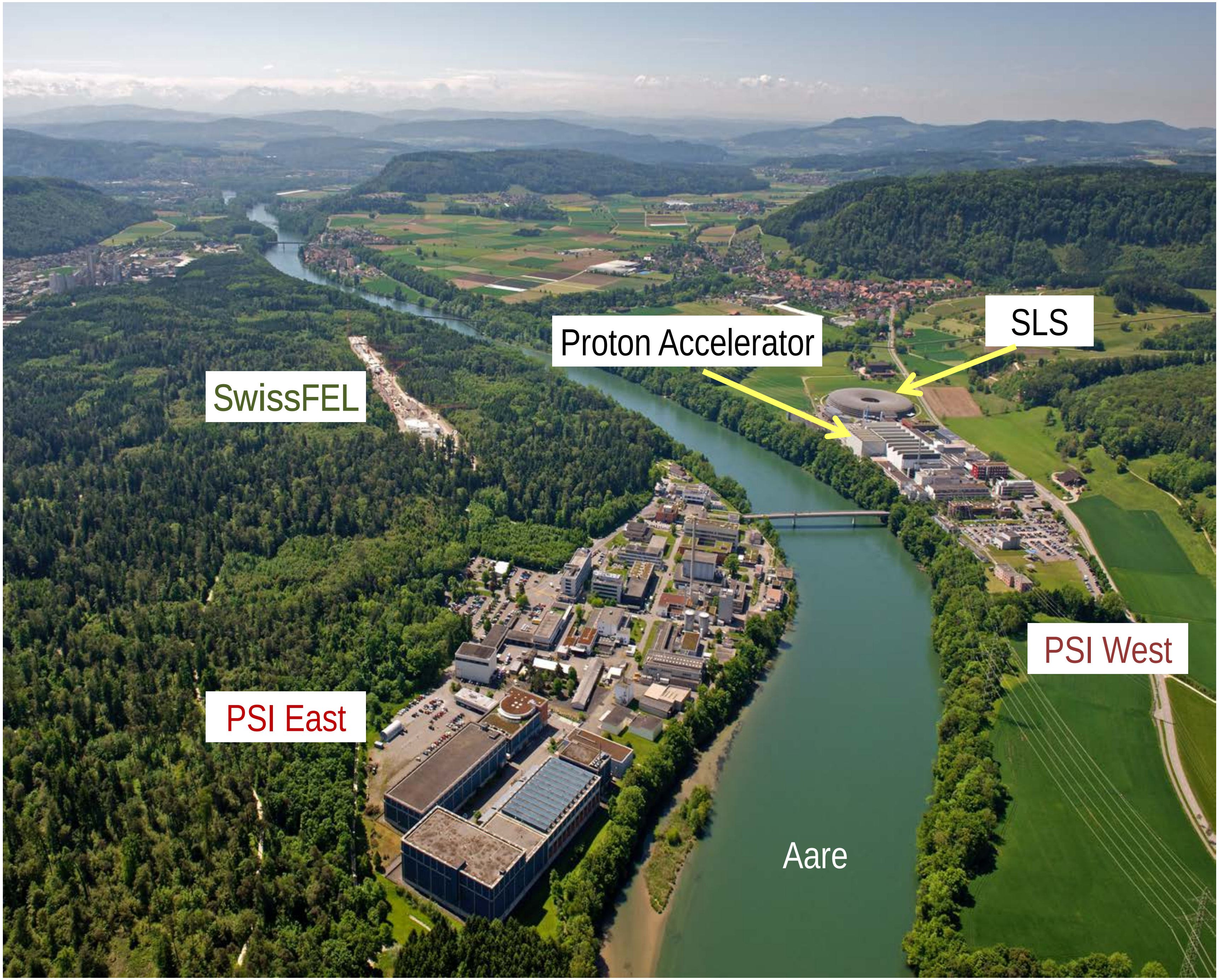
- Introduction/ SwissFEL Project Overview

- SwissFEL Beam Diagnostics Tools

- Summary/Conclusions

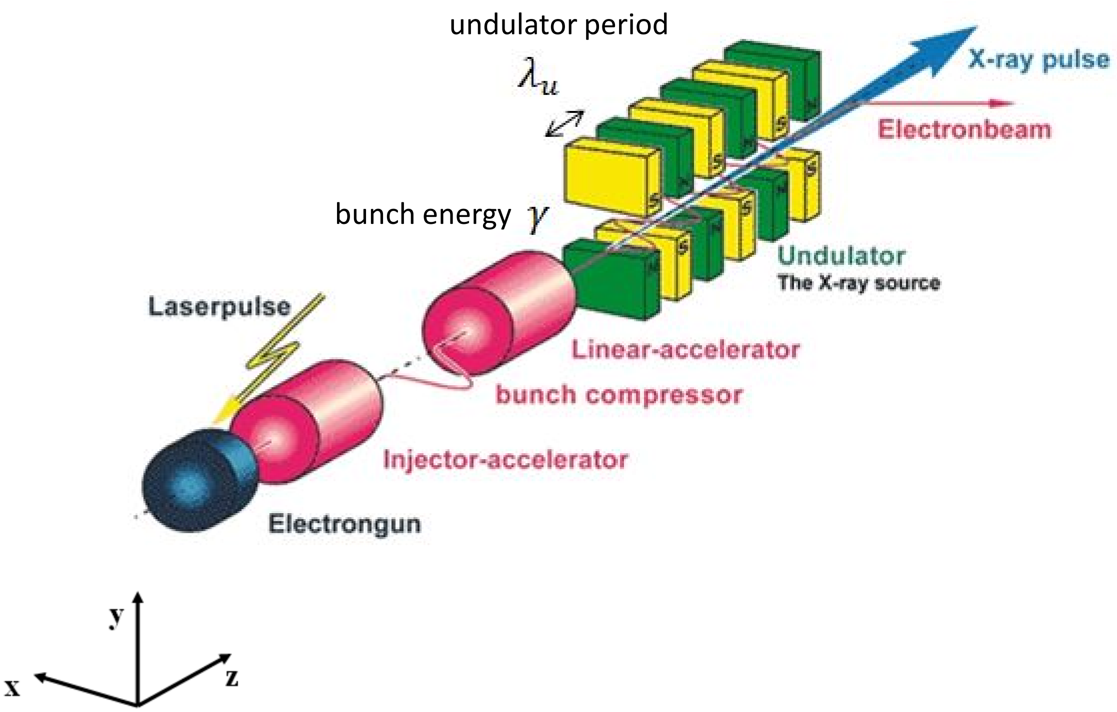
SwissFEL location

Paul Scherrer Institute, near Zurich, Switzerland, Europe


Proton Accelerator
SLS
SwissFEL
PSI West
PSI East
Aare

SwissFEL – a hard X-ray (0.1 nm) SASE FEL at PSI, Switzerland

SASE* (Self Amplified Spontaneous Emission) FEL



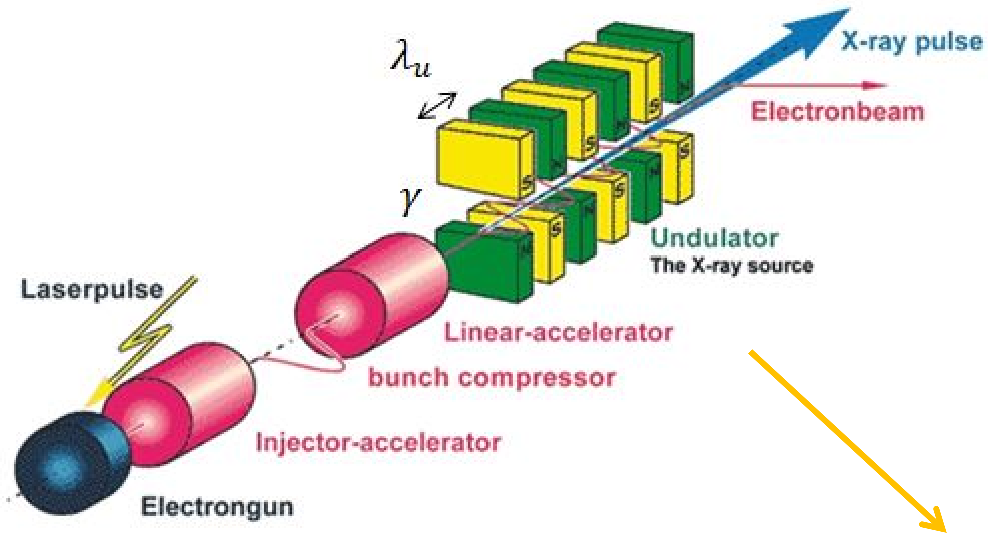
- relativistic electron bunch
- a (long enough) undulator

$$\vec{B} = \left(0, \vec{B}_u \sin k_u z, 0\right)$$

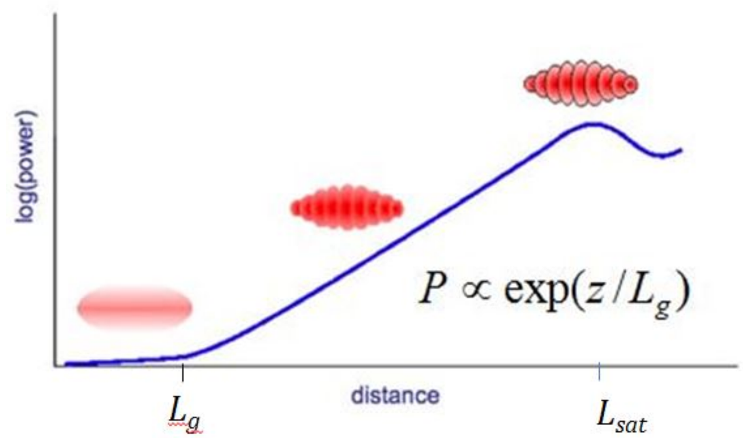
$$k_u = \frac{2\pi}{\lambda_u}$$

*) Kondratenko, Saldin 1980
Derbenev, Kondratenko, Saldin 1982
Bonifacio, Pellegrini, Narducci 1984

SASE (Self Amplified Spontaneous Emission) FEL

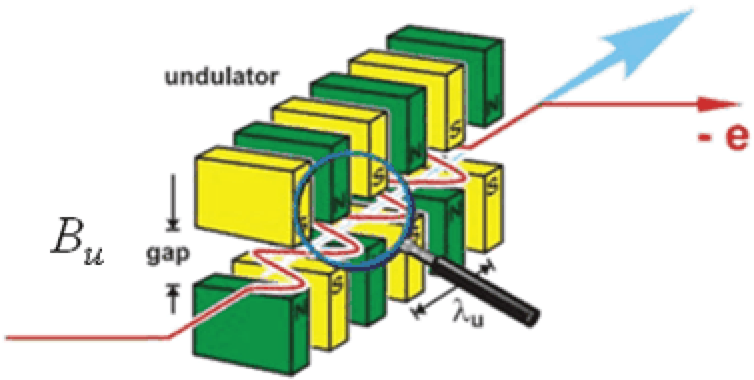


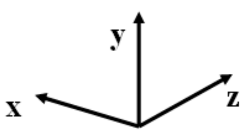
- In the undulator, the bunch is modulated by its own synchrotron radiation field
- Electrons are "self-organized" in micro-bunches, which radiate coherently
- The total radiated power grows exponentially until it reaches saturation



SASE FEL performance conditions

$$\vec{B} = \left(0, \vec{B}_u \sin k_u z, 0\right)$$





$$x(z) = x_0 \sin k_u z$$

$$k_u = \frac{2\pi}{\lambda_u}$$

- **A resonant condition in the undulator**

$$\lambda_0 = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

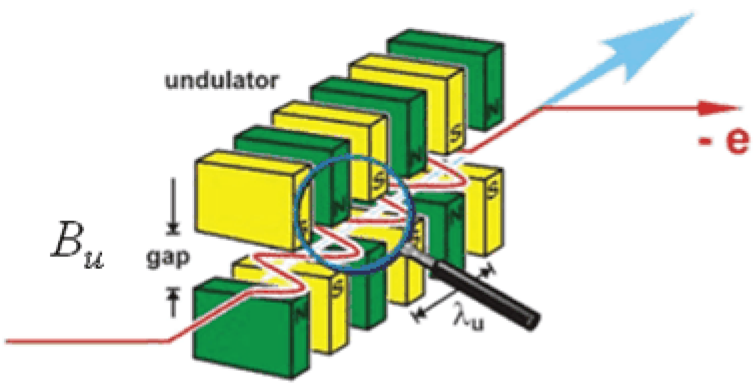
$$K = \frac{eB_u\lambda_u}{2\pi mc} \approx 0.93\ \lambda_u\ [\text{cm}]\ B_u\ [\text{T}]$$

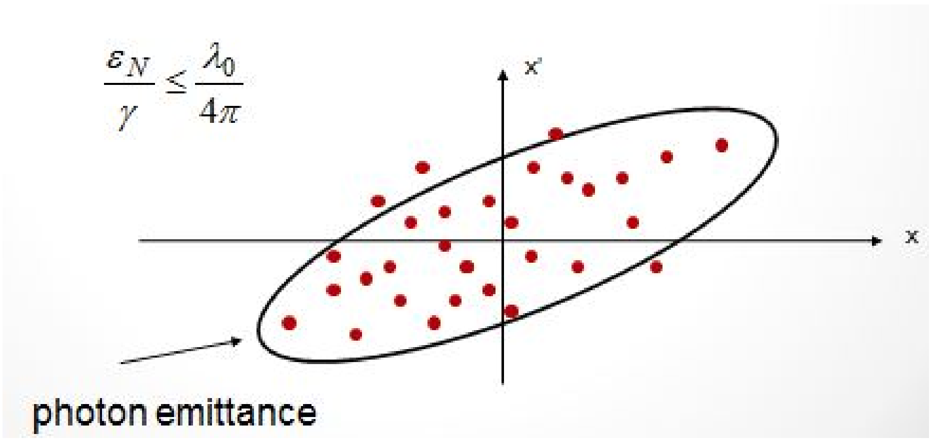
undulator parameter

Parameters for lasing at 1 Å

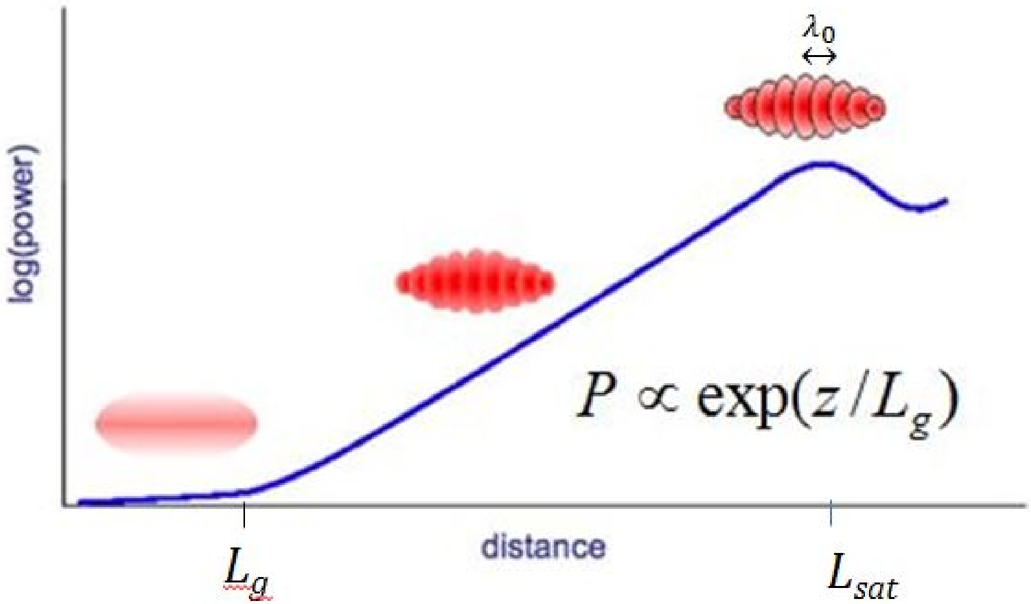
Beam energy	5.8 GeV
λ_U	15 mm
K	1.2

- **A sufficient overlap between the electron bunch and its radiation field**





A bright source with small $\boldsymbol{\varepsilon_N}$
or high energy



$$L_{sat.} \sim \frac{1}{\rho}$$

SwissFEL (0.1 nm) - 45 m

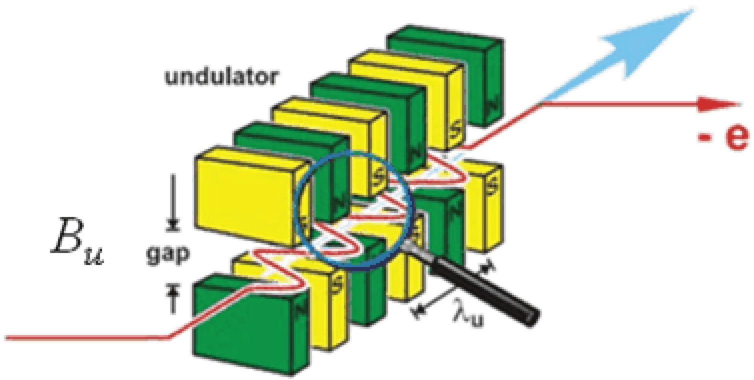
$$\rho \sim \left[\frac{I_{peak}}{\sigma_x \sigma_y}\right]^{\frac{1}{3}}$$

FEL parameter

for VUV FELs ~ 0.01-0.001
SwissFEL (0.1 nm) ~ 0.0003

$$L_g = \frac{\lambda_u}{4\sqrt{3}\pi\rho}$$

So, SASE FEL requires

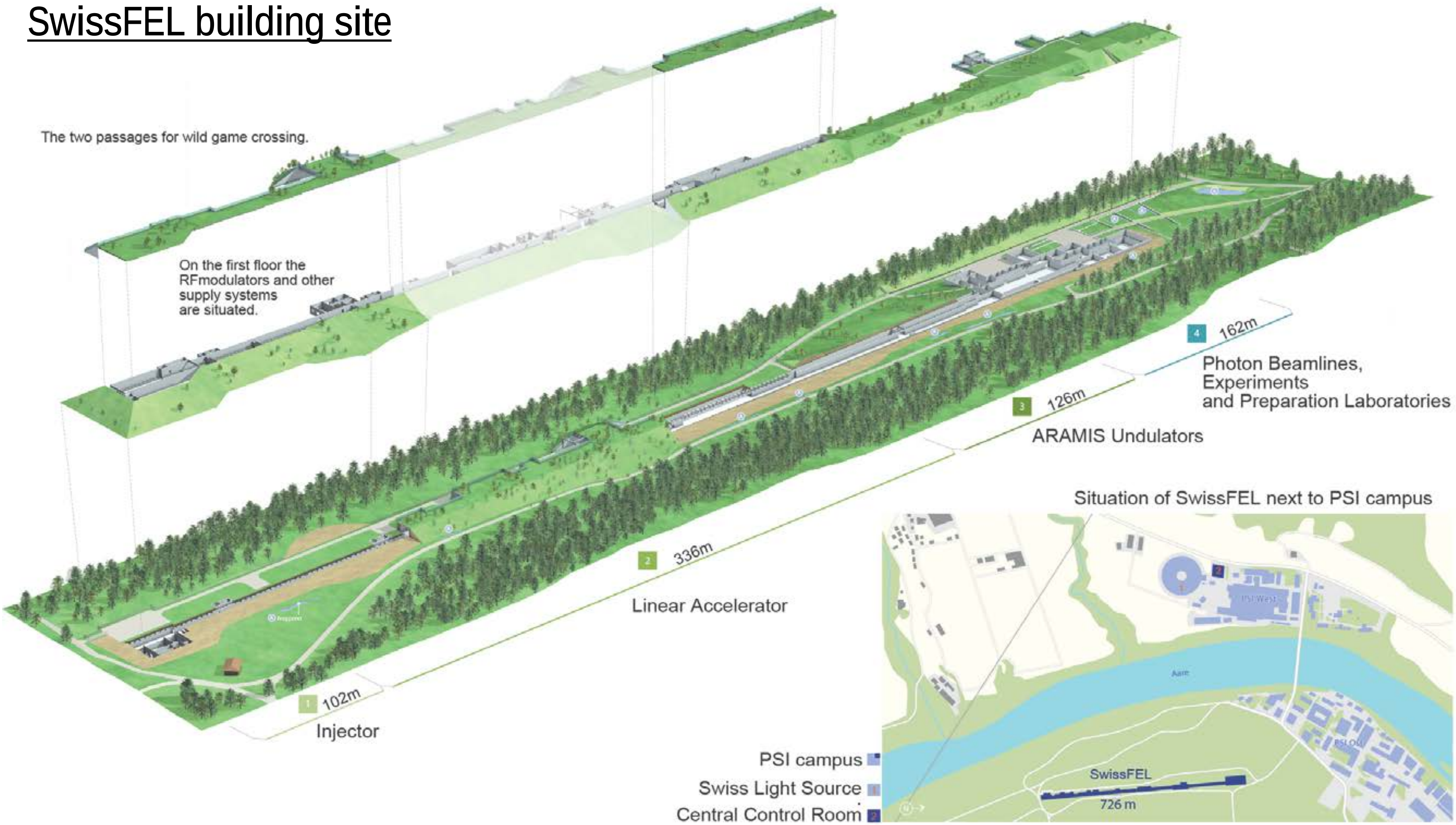


- Small bunch length
- Small transverse bunch size
- Very precise beam steering through the accelerator and (long) undulator

SwissFEL – a "compact" hard X-ray SASE FEL @ PSI, Switzerland

→ building length: ~700 m → construction period: 2012 – 2017

SwissFEL building site



X-FEL Facilities

	LCLS (USA)	SACLA (Japan)	European XFEL	SwissFEL (CH)
Start of operation	2009	2011	2017	2017
Length [km]	3.0	0.75	3.4	0.75
Beam energy [GeV]	13.6	8	17.5	5.8
Min. wavelength [nm]	0.15	0.1	0.1	0.1
Peak brilliance at λ_{min} [10^{33} photons/s/mm²/mrad²/0.1% BW]	2.4	5.0	5.0	1.3

SwissFEL has the lowest beam energy (optimized for 1Å)

Advantages: Compact and affordable for Switzerland

Challenges : More stringent requirements for the beam quality, mechanical and electronic tolerances

For availability/costs reasons the injector is *European S/X band*,

whereas the linac is *US C band*

SwissFEL frequencies

Frequencies in MHz

		«European»	«American»	f_b=142.8
Injector	S-Band	2997.912 Already procured	2856	2998.8 ($21xf_b$)
	X-Band (4 x S-band)	11991.648 Already procured	11424	11995.2 ($84xf_b$)
Main linac	C-Band (2 x S-band)	5998.524 requires development of klystron with PSI presently the only customer	5712 Klystron available almost "off the shelf" Spring8, KEK, LNF are already customers	5712 ($40xf_b$)

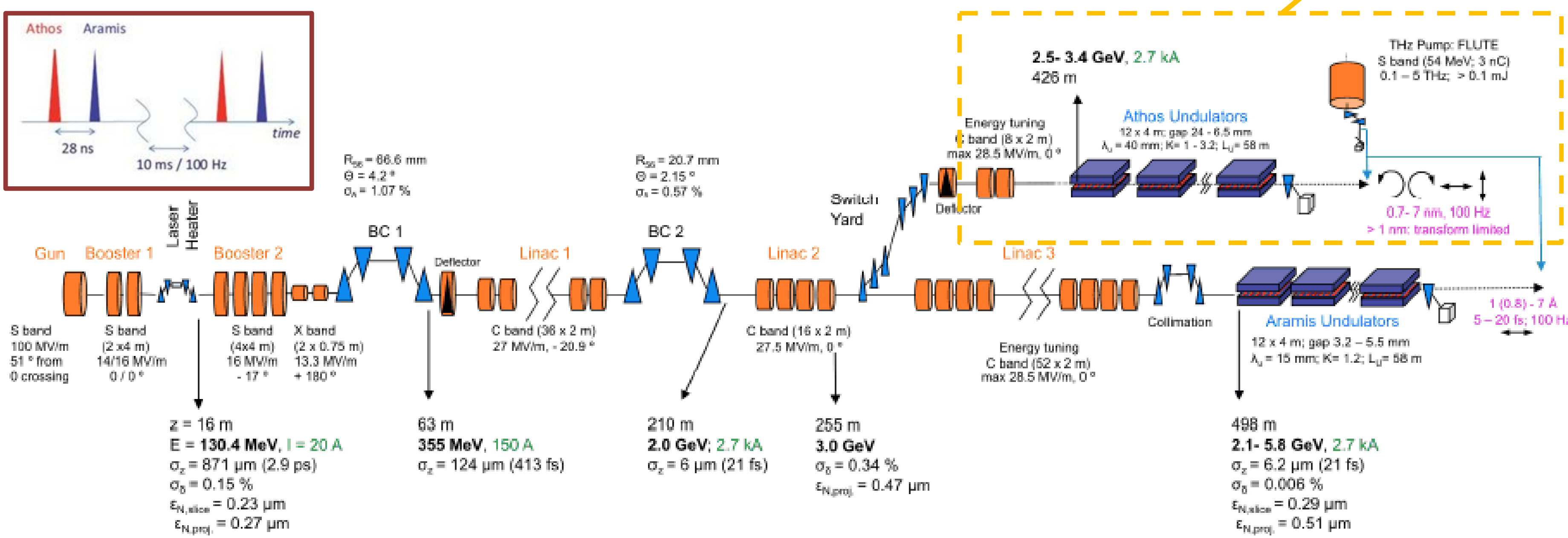
Common sub-harmonic 142.8MHz, minimum bunch spacing 7 ns

SwissFEL Highlights

- ***Two FEL Beamlines:***
  - *Hard X-ray Beamline Aramis: SASE FEL (1 – 7 Å), tuning mostly by energy*
  - *Soft X-ray Beamline Athos: SASE FEL (7 – 70 Å), seeded FEL (10 – 70 Å), tuning by gap and energy*
  - *Possible future extension for another hard or soft X-ray beamline (Porthos)*

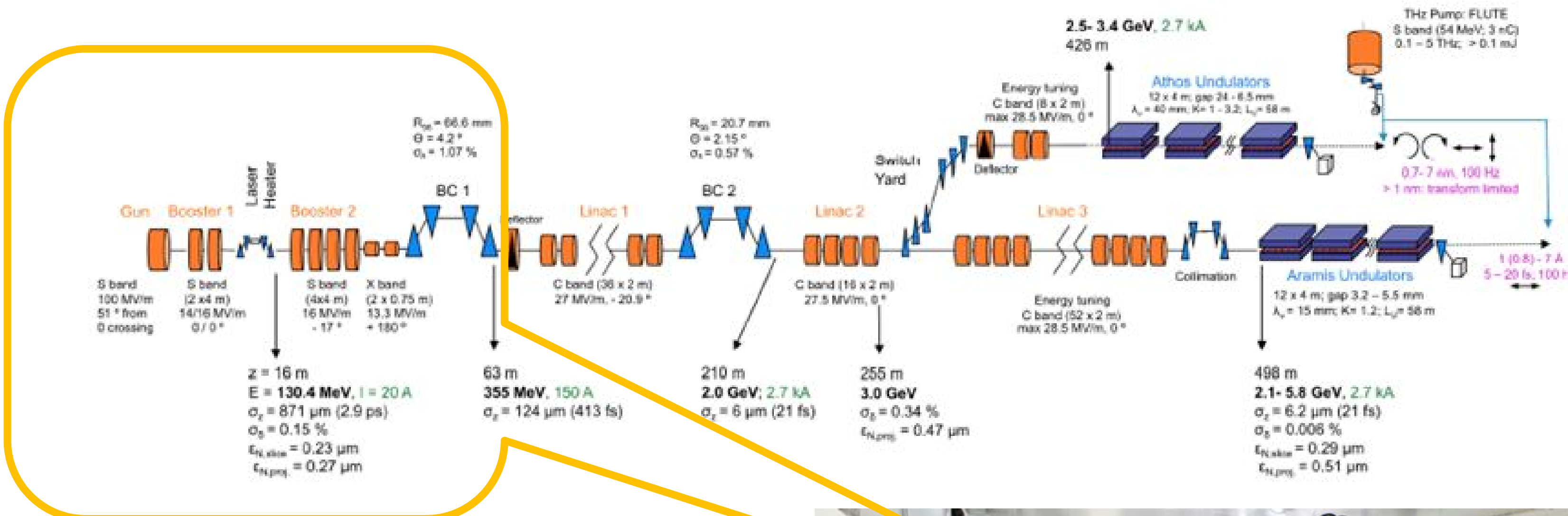
- ***Electron Beam**:*
- 10 – 200 pC, 2.1- 5.8 GeV, 1.5 – 3 kA, 0.15 – 0.43 mm mrad, Energy spread 300 keV

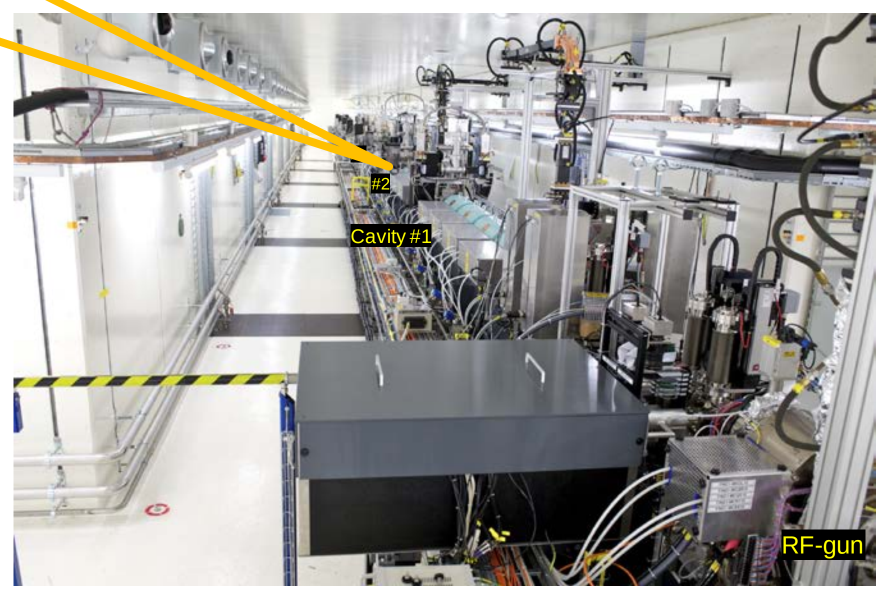
- ***RF:***
  - *2.5 cell S-band RF Gun, S-band booster linac, X-band linearizer, C-band linac*



SwissFEL Machine/Beam Diagnostics Design/Development Resources

SwissFEL Injector Test Facility (SITF): 250 MeV Machine





In operations from 2010-2014

Other FEL Facilities Worldwide

- LCLS, USA
- SACLA, Japan

- FERMI, Italy
- FLASH, Germany

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 ($\varepsilon_n \geq 180$ nm rad) 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)

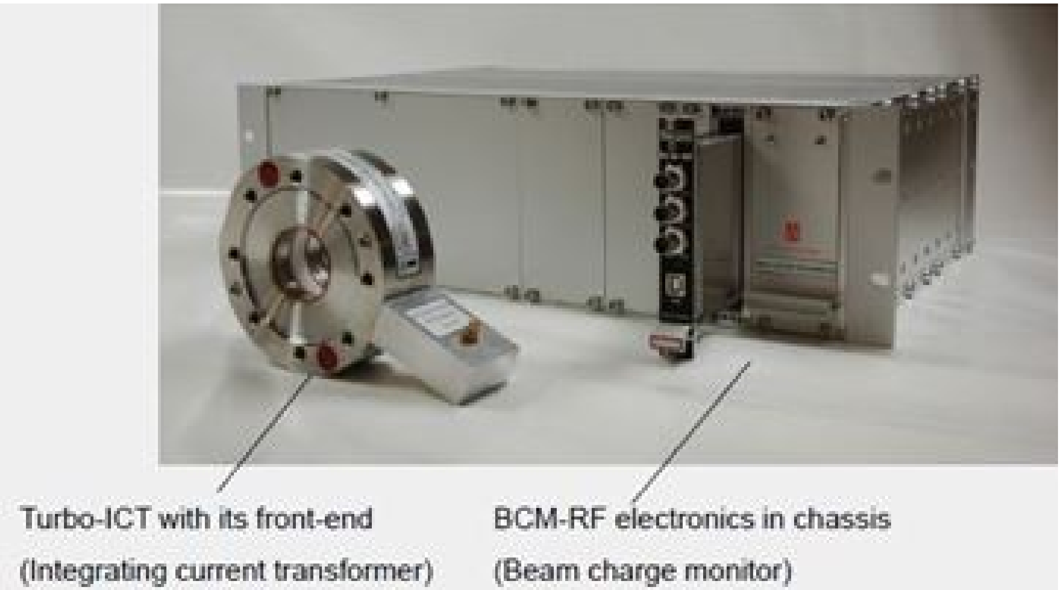
SwissFEL Key Parameters	Operation Modes	
	Long Bunch	Short Bunch
Bunch Length	20 fs (rms)	2.5 fs (rms)
Comp. Factors	125	240
Norm. $\varepsilon_{h,v}$	430 nmrad	180 nmrad
Timing Stability	Jitter	Drift
Sync. System	< 10 fs	< 20 fs / day
Bunch Arrival	< 10 fs	< 10 fs / day

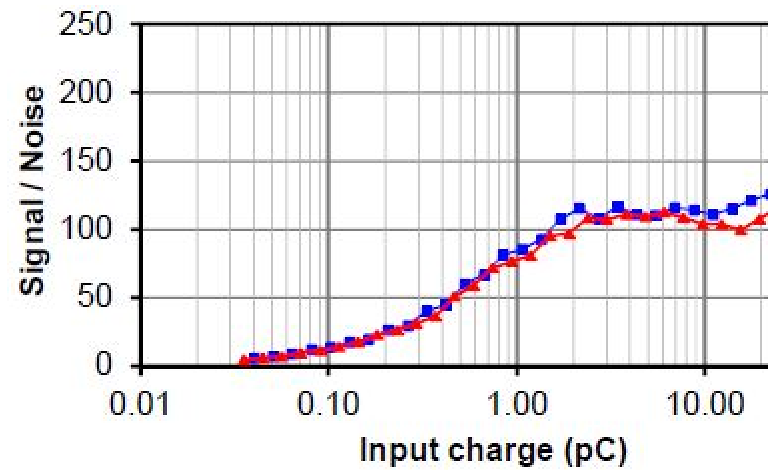
Beam Charge Monitors

Main SwissFEL requirements:

- **Absolute charge (10-200 pC) measurement accuracy – 1%**
- **2-bunch resolving capability**

Bergoz Turbo-ICT-2

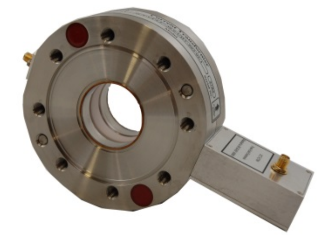


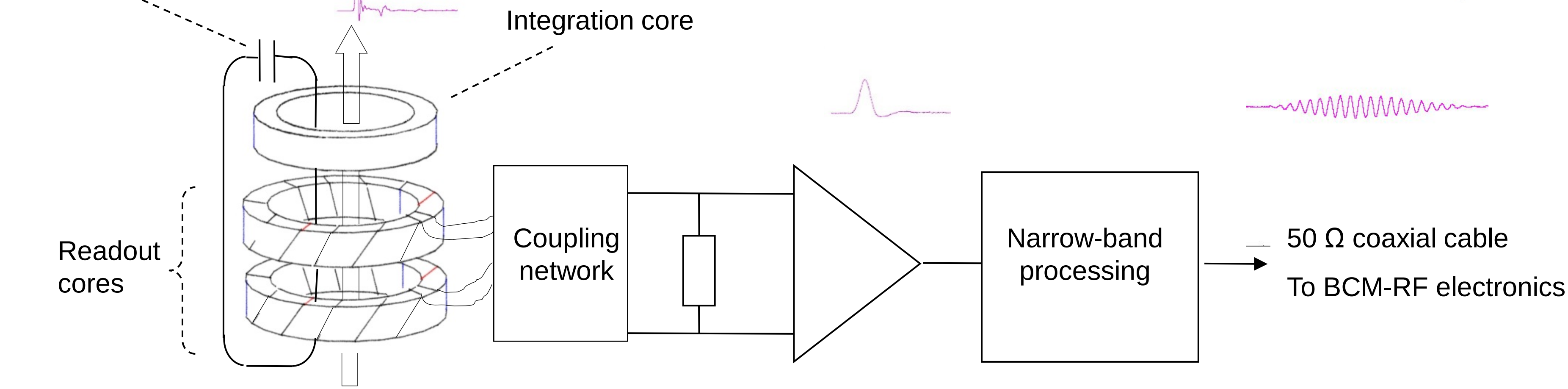


blue squares – first bunch
red squares – second bunch

- Delivered as a fully calibrated device
- Not sensitive to the dark current due to its fast readout of the beam induced current (3 ns) at higher bandwidth

Turbo-ICT Principle





- Integration time is reduced by 25 compared to traditional ICT. Bandwidth increase is achieved by using low-loss core alloy.

⇒ Signal increases by 25 and noise by √25. Hence signal over noise ratio increases by 5.

- Multiple cores could be used to catch more signal from beam. The core windings outputs are combined to optimize the power transmission from cores to front-end amplifier.

- Readout cores are coupled to a low noise amplifier. Impedance is chosen to optimize signal over noise performance.

- Narrow-band processing. The wide-band signal from the amplifier is converted to a 100-325 MHz single tone resonance. Apex amplitude is proportional to the bunch charge.

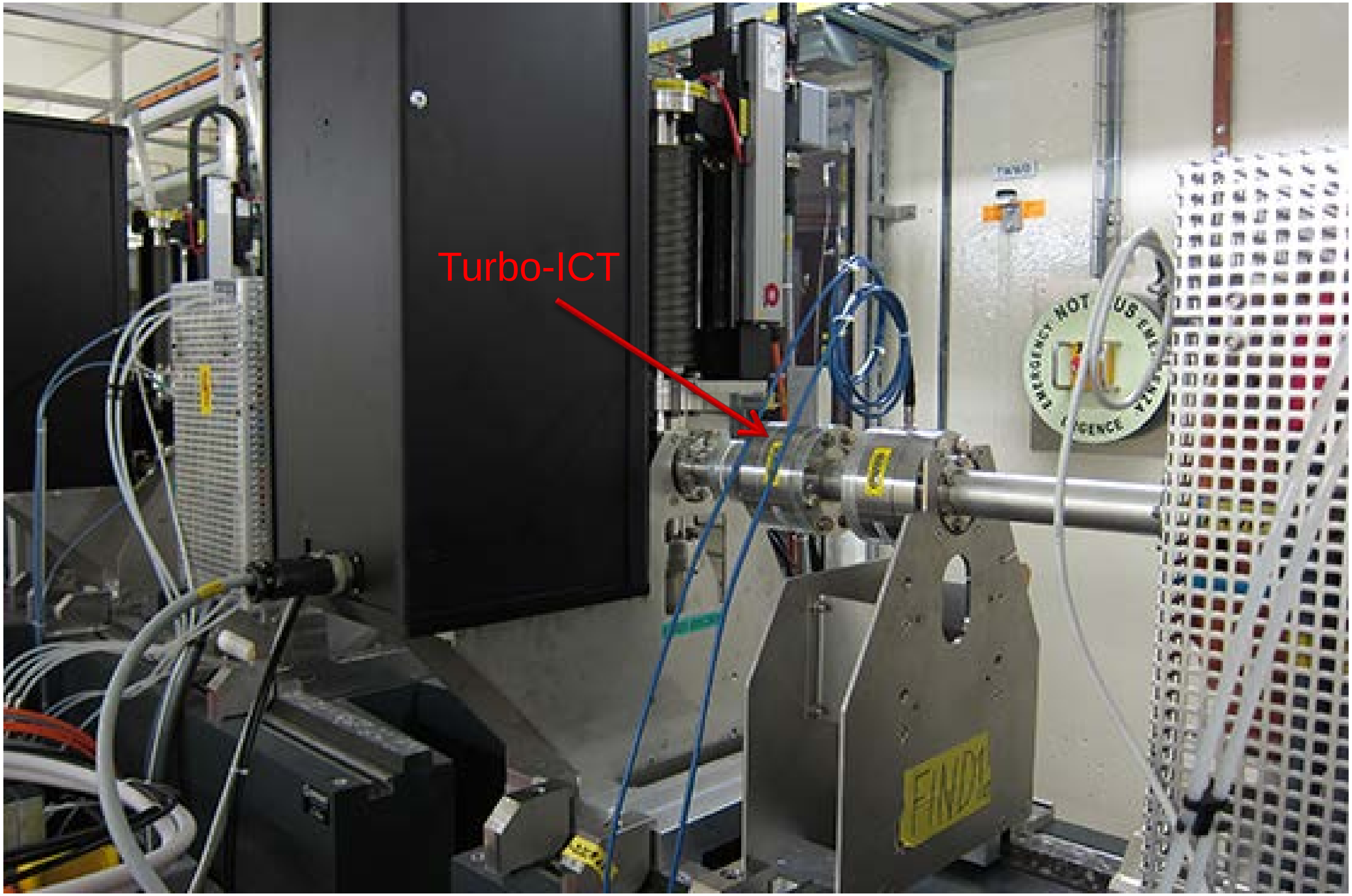
⇒increases noise immunity.

⇒ decreases insertion losses in cable.

⇒ improves impedance matching.

Bergoz Instrumentation

Turbo ICT Installed in SITF



Beam Position Monitors

Requirements / Specifications

Parameter	Injector	Linac & TL	Undulators
Pickup Length	250 mm	100 mm	100 mm
Inner Beam Pipe Aperture	38 mm	16 mm	8 mm
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%
Nominal Charge	10-200 pC		
# Bunches per Train	1-3		1
Max. Bunch Train Rep Rate	100Hz		
Min. Bunch Spacing	28 ns		-

Solution

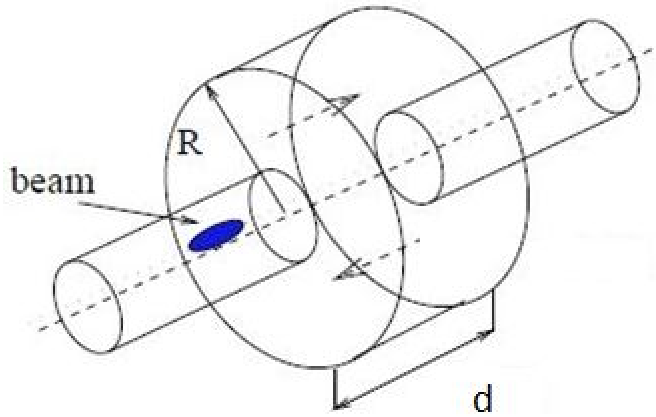
Pickups:

- Use only cavity BPMs (based on E-XFEL/SACLA design optimized for low charge operations) to minimize manpower & to get a homogeneous system.

Electronics:

- Based on E-XFEL electronics (PSI, Swiss in-kind contribution to the European project).
  Small modifications are made to meet SwissFEL specs.

Resonant Cavity in Accelerators

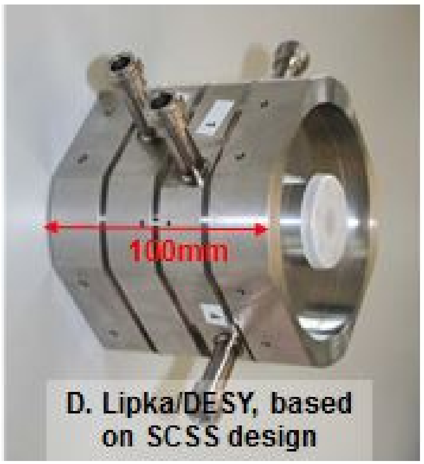


- Passing a pillbox-like resonant cavity the electron bunch excites several resonance modes

  -- short bunches deliver a wide spectrum of frequencies

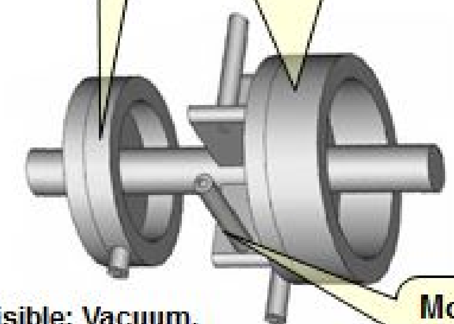
RF-BPM (similar designs for SCSS, European-XFEL, SwissFEL)

Dual-resonator,
coaxial connectors,
mode-selective
(3.3GHz)



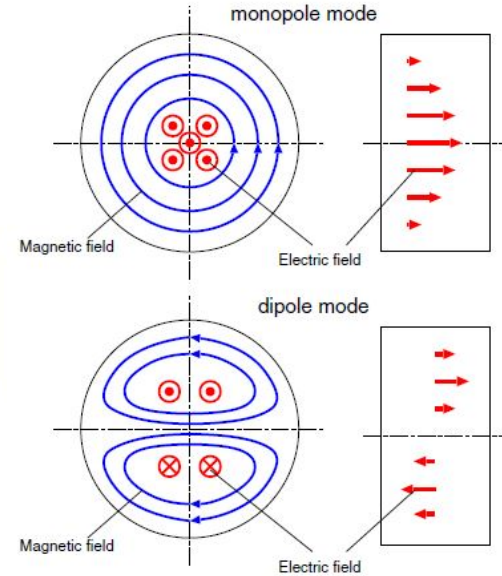
Reference cavity (1 connector): 3.3GHz signal ~ bunch charge

Position cavity (4 connectors) : 3.3GHz signal ~ position * charge



Visible: Vacuum, couplers

Mode-selective couplers suppress undesired other modes

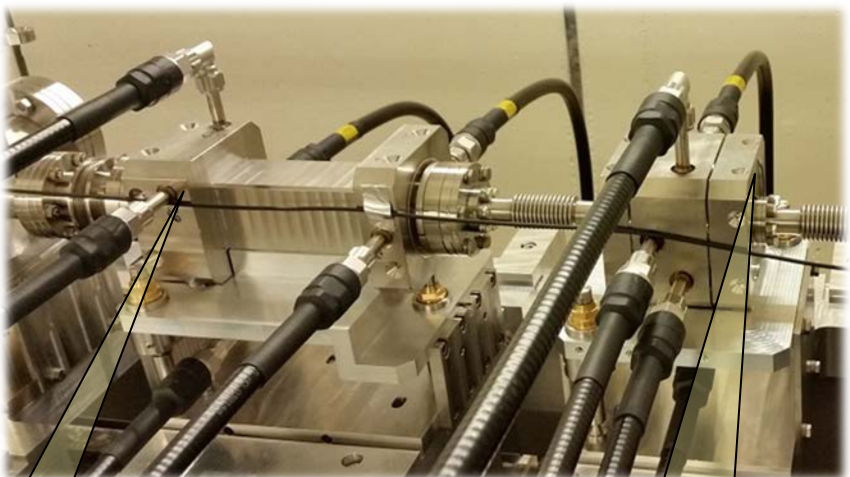


electronics

Beam Position = k * (V_{Pos_Cav}/ V_{Ref_Cav}). Factor k: Not fixed, variable via attenuator.

*The identical frequencies of the position and reference cavities modes minimize the impact of the frequency dependent gain drift on the position readings.

SwissFEL Beam Position Monitor System

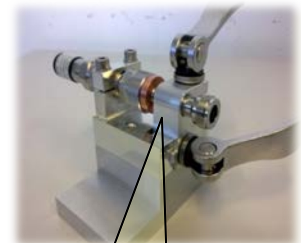


BPM38 (stainless steel)

Electronics (BPM16+38)

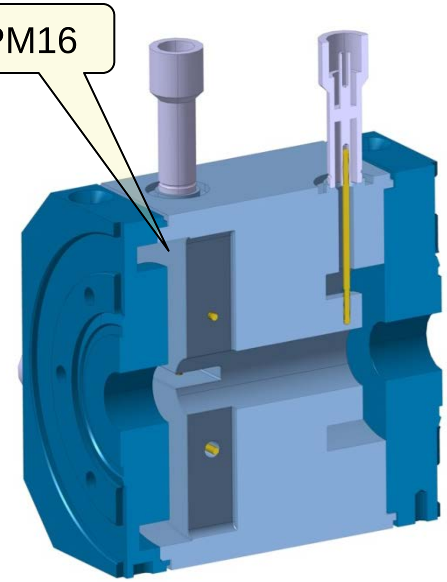
BPM8 (copper-steel hybrid)

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



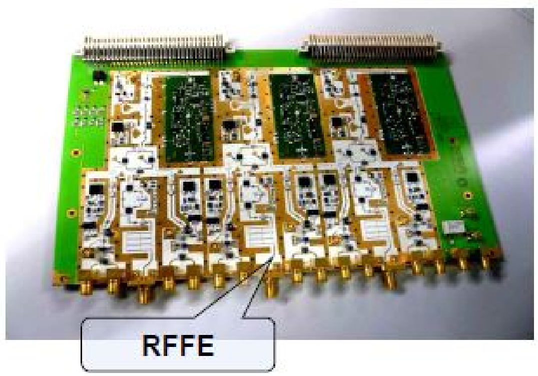
Feedthrough Test Adapter

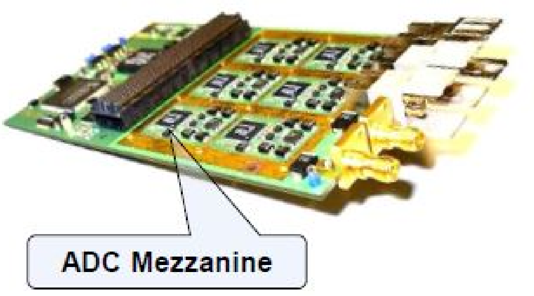
BPM16



Cavity BPM Signal Processing Electronics as a Modular Topology of SwissFEL Diagnostics Systems

Based on the latest FPGA technology (Kintex-7/Artix-7)

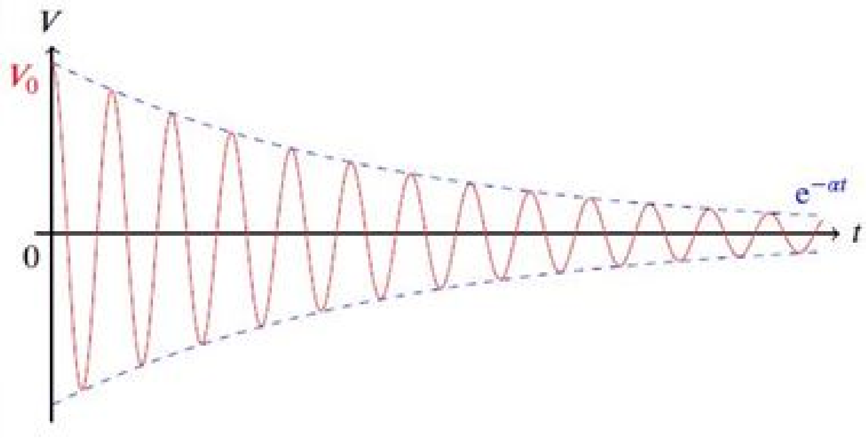




SwissFEL Beam Position Monitor System

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		-

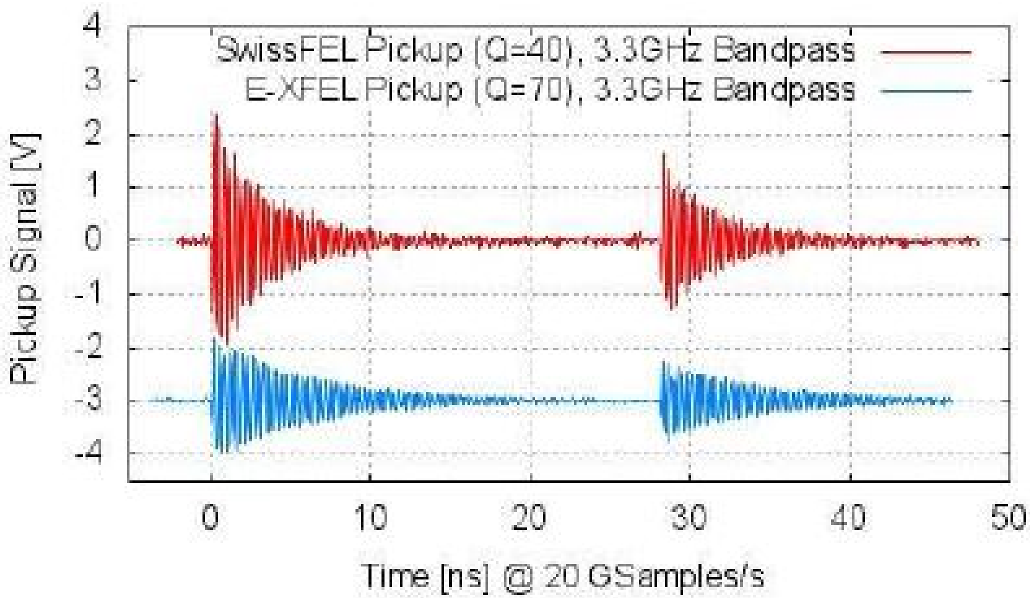
Beam Tests: sub-µm position resolution and ~ 10 fC charge noise



The typical output signal from a cavity.

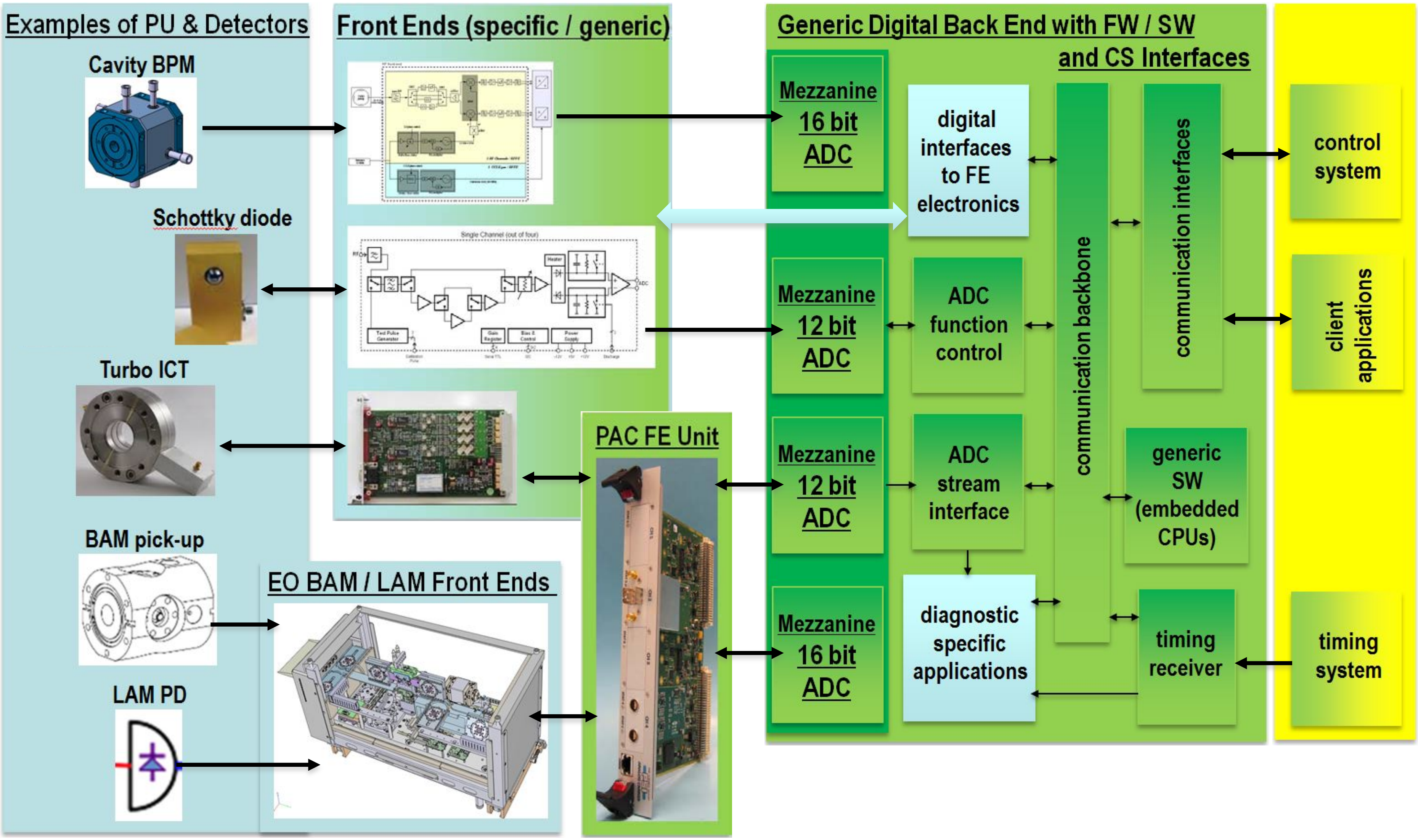
$$Q_L = \frac{\omega W}{P_0 + P_{ext}} = \frac{\omega W}{-\frac{dW}{dt}} = \frac{\omega}{2\alpha}$$

smaller Q_L for higher damping rate

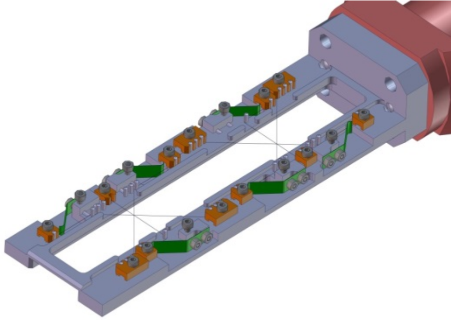


Beam Position Monitor Project Outcome

Standard SwissFEL Beam Diagnostics Electronics

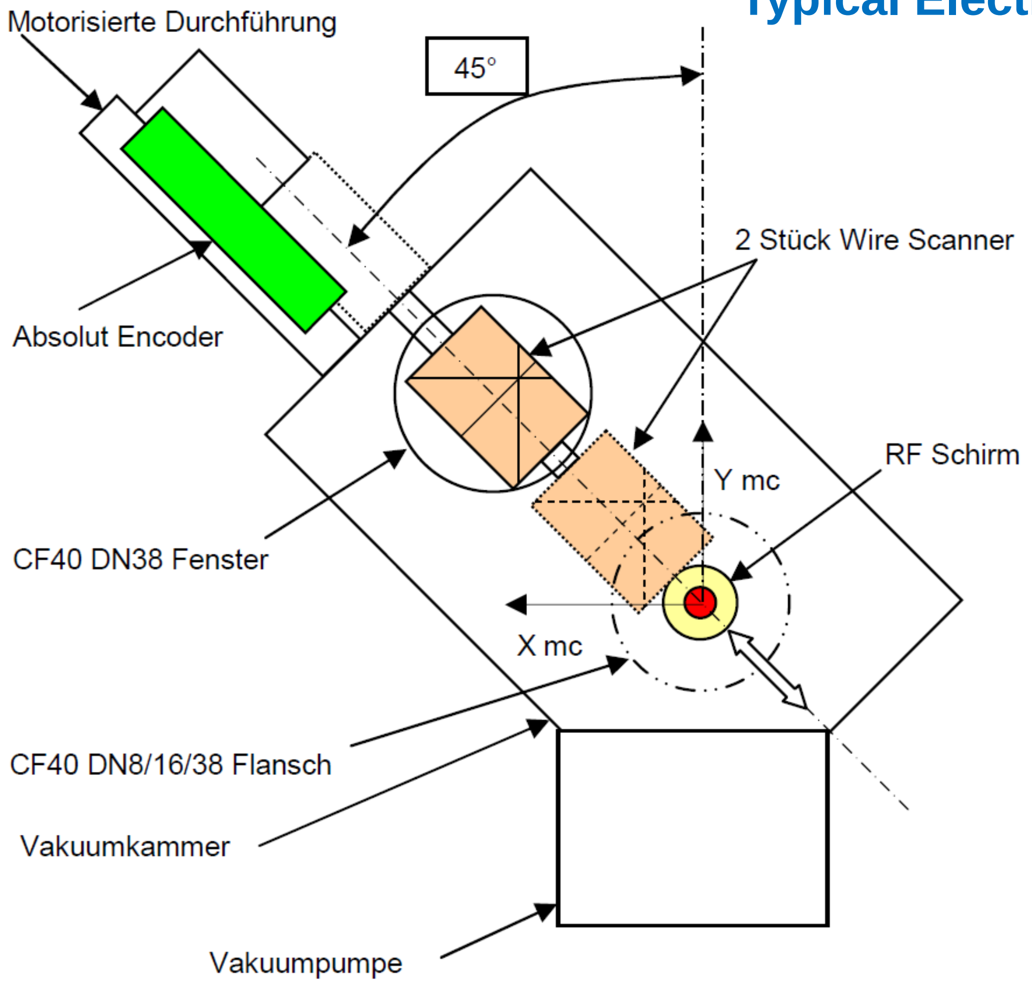


Transversal Beam Diagnostics Monitors



Wire Scanners

Wire Scanner Characteristics



Typical Electron Beam Size: 5-500 μm

Number of Wires per Frame:

- 3 + 3 (spare or different resolution)
- 3 possible wire separation (to speed-up the scan time)
- X, X-Y& Y scan in sequence

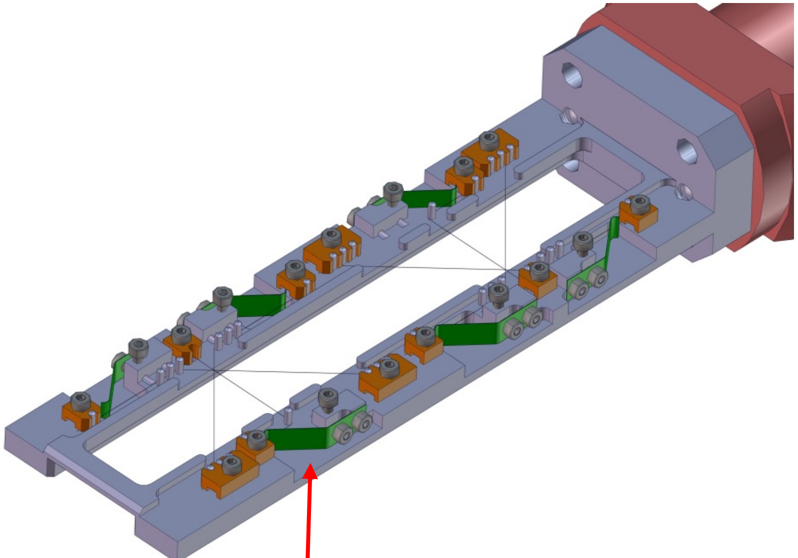
Wire Specifics and Resolution:

- W (Tungsten) wires
- Diameter = 5-25 μm
- Resolution (RMS)= 1.5-6.5 μm

Encoder Resolution:

- 0.1 μm (absolute position)

Technical Realization

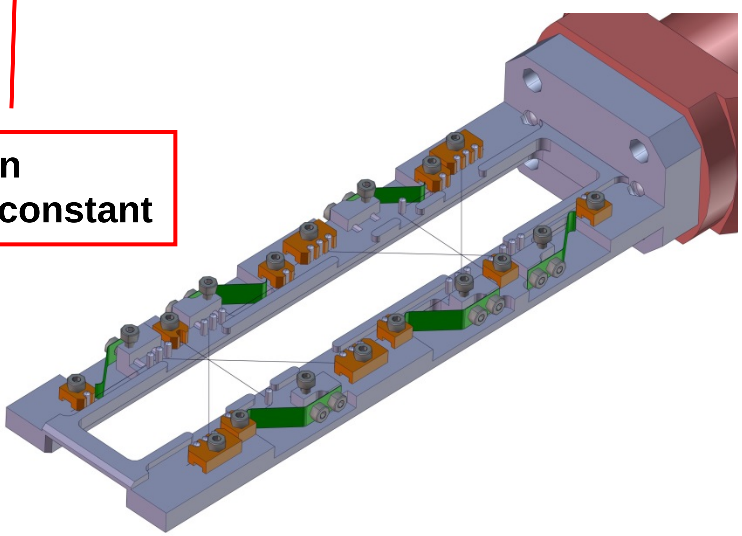


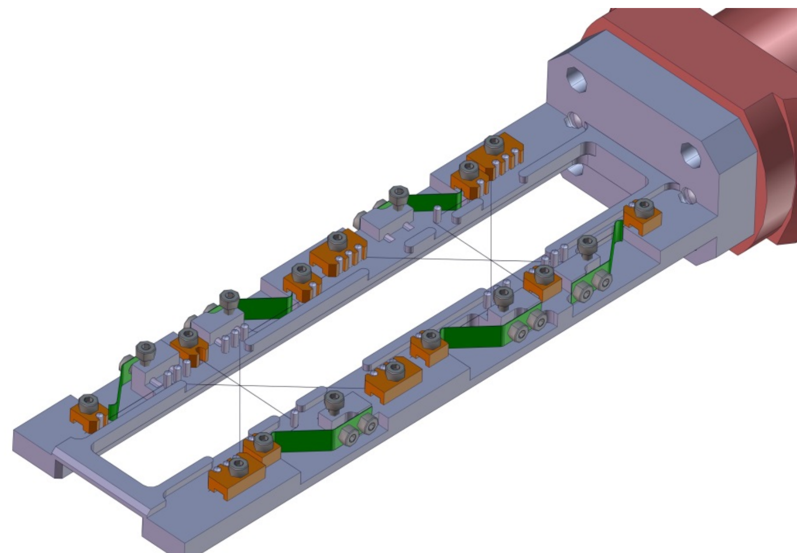
3 different pins to allocate the wire

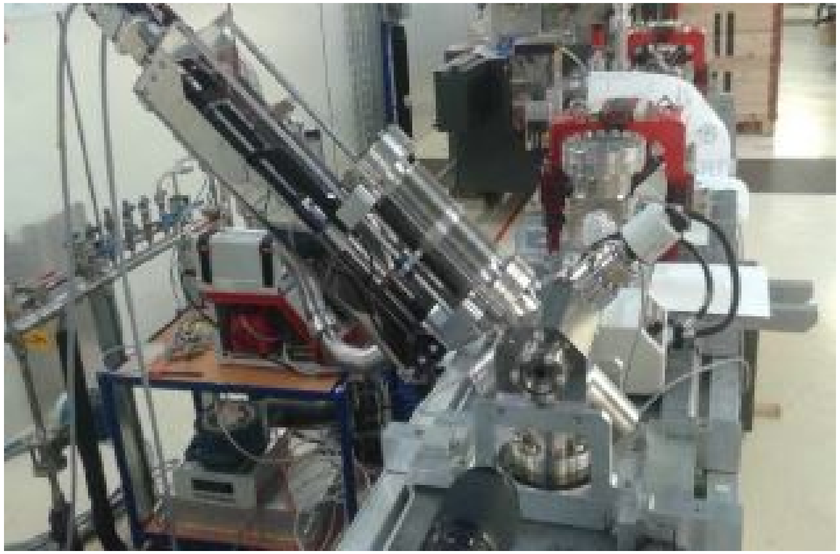
3 different wire separations

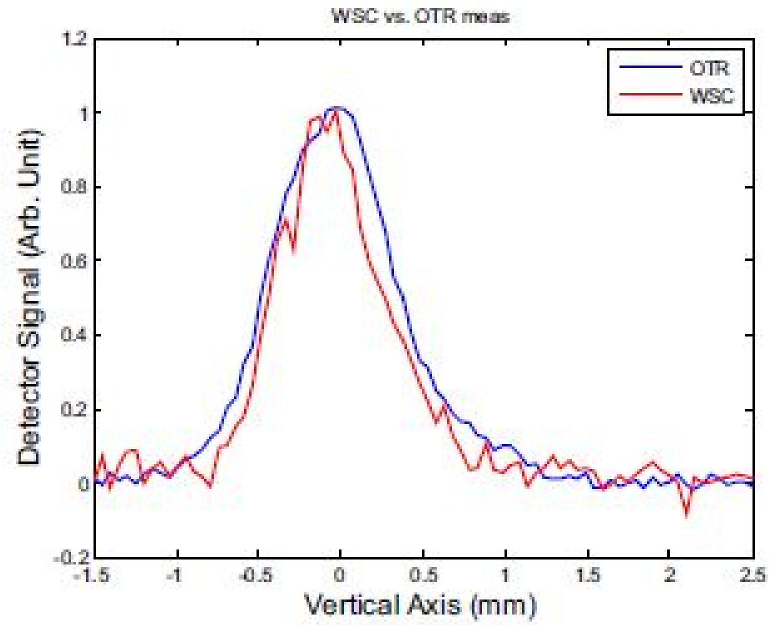
3 different scan times

Spring to maintain
the wire tension constant









It was demonstrated that in the wire velocity range 0.2-2 mm/sec the wire vibration is below the intrinsic resolution limits.

Al:Si wires of 12.5 micrometer thickness are possible candidates for the undulator areas.

Beam Loss Monitors

Localized BLMs (wire scanner support)

- Must provide online beam size measurements by recording losses due to wire insertions

- Requirements

Full beam loss event / bunch	**10…200 pC**
Wire scanner operations	**0.1…20 pC**
Operational requirements:	**Synchronized DAQ @ 100 Hz**
	Interface to Machine Protection System (all BLMs)
	Ability to resolve 2 bunches

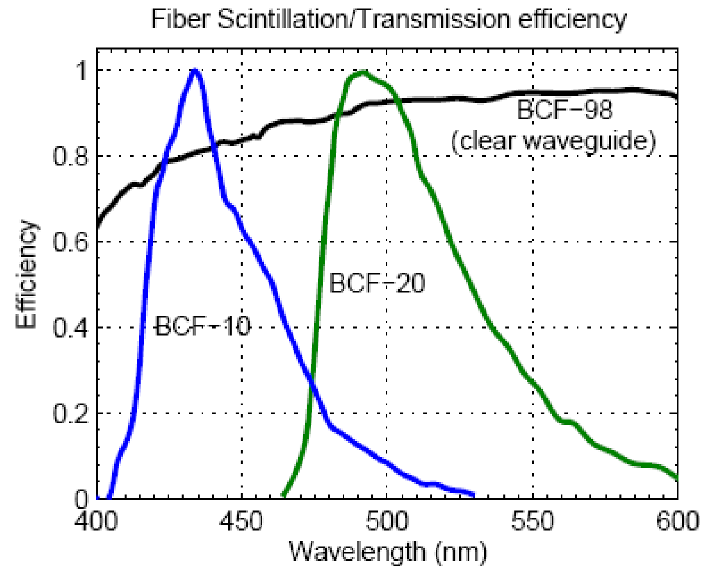
Optical Fiber Based Systems

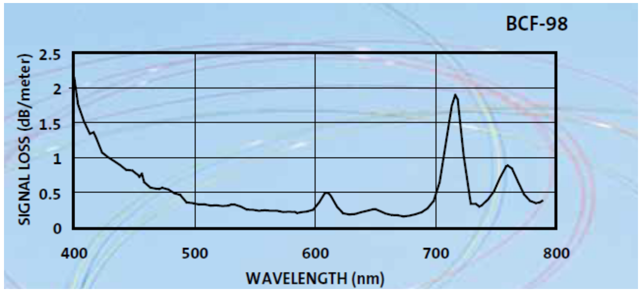
- Scintillating Plastic Optical Fibers (POF)
- Flexible
- Cost effective
- Clear waveguides can be used to carry signals out of the accelerator tunnel
- Radiation resistant (>20% trans. scint. loss) > 400 Rad for various scintillating POF

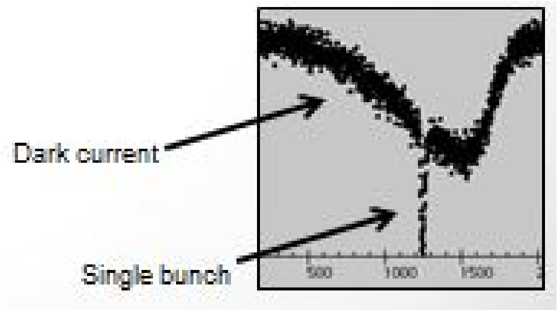
  → radiation hard (1 MRad) versions also exist

Optical Fiber Based Systems

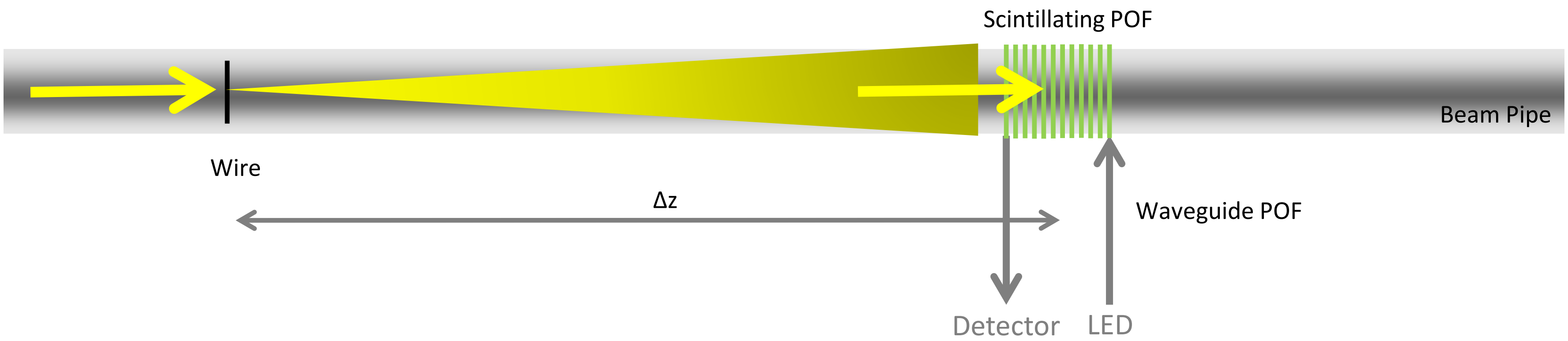
- POF fibers for SwissFEL – Saint Gobain Crystals
  - 1 mm diameter polystyrene scintillator fibers
  - Characteristic signal decay time ~ 2.7 ns
  - Emission wavelength: visible
  - Photon yield in plastic scintillator: 8000/MeV
  - 1/e length ~ 3.5m
  - Core refractive index 1.5-1.6
- Can differentiate signal from the dark current
- Can detect wire losses down to the input bunch charge of 1pC

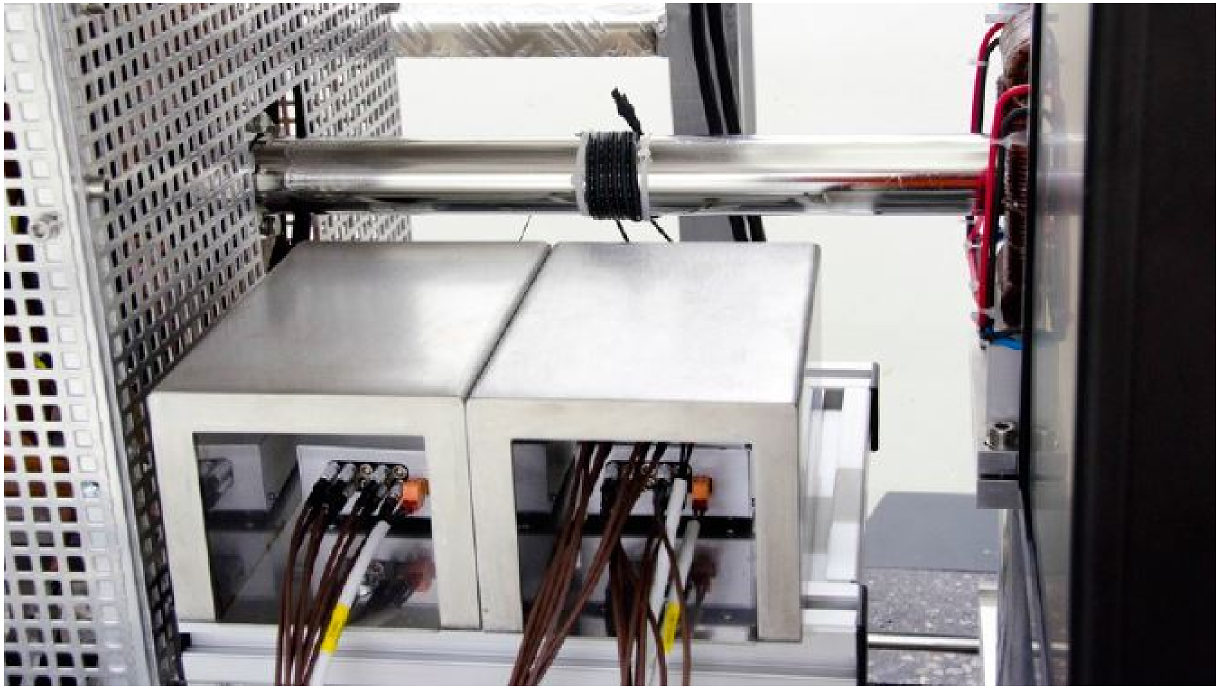




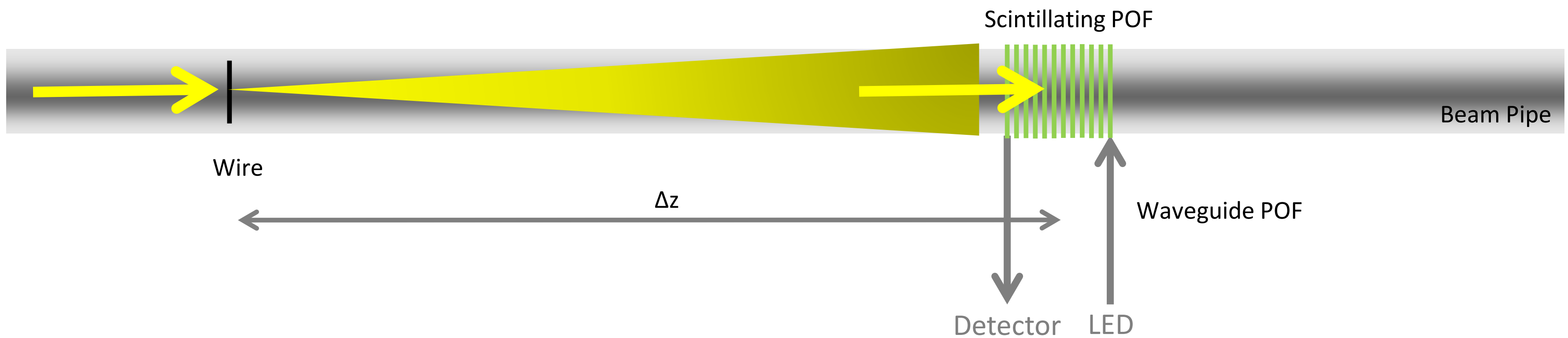


Localized BLMs



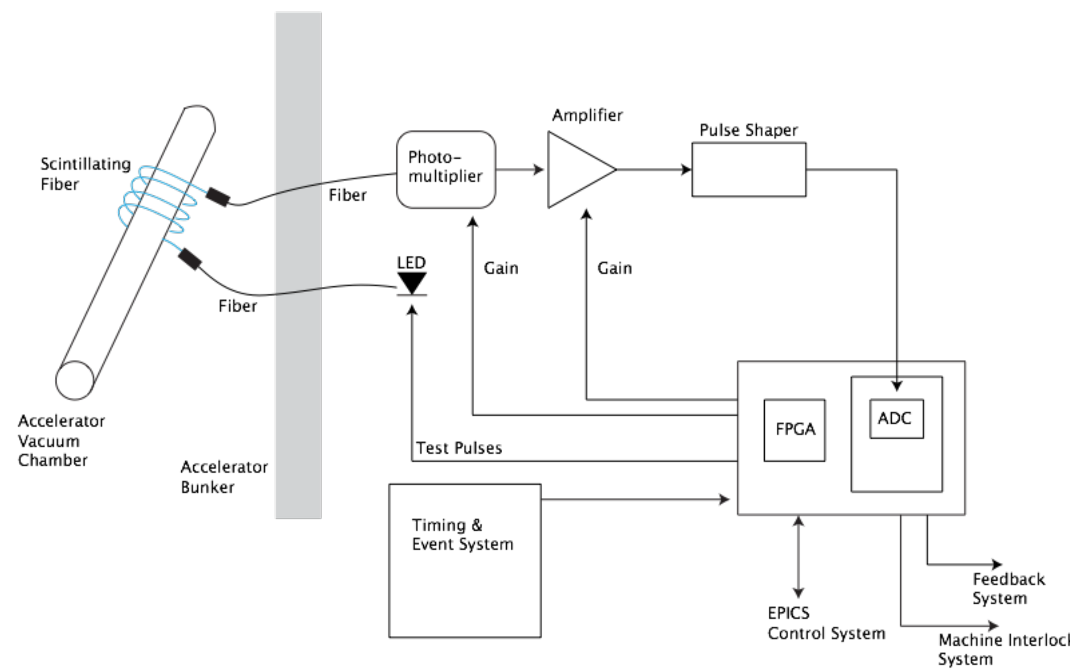


Localized BLMs



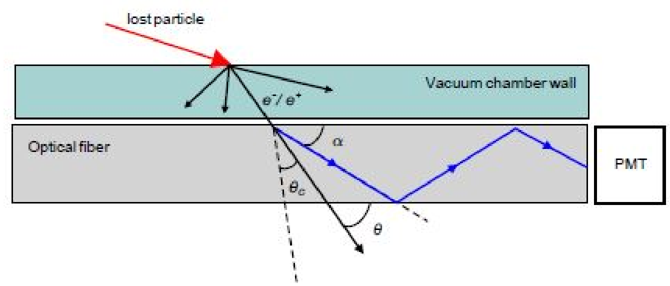
Fast PMT - Hamamatsu H10720

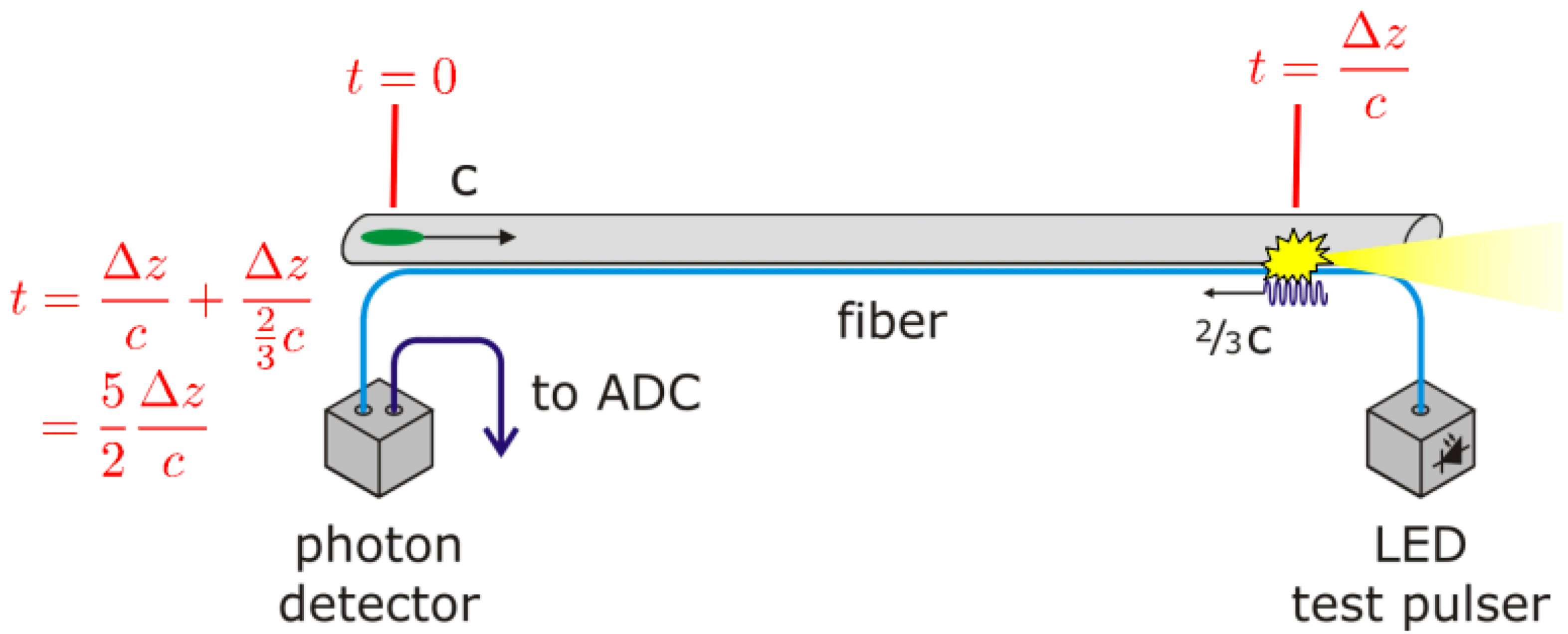
Provide 28 ns bunch resolution

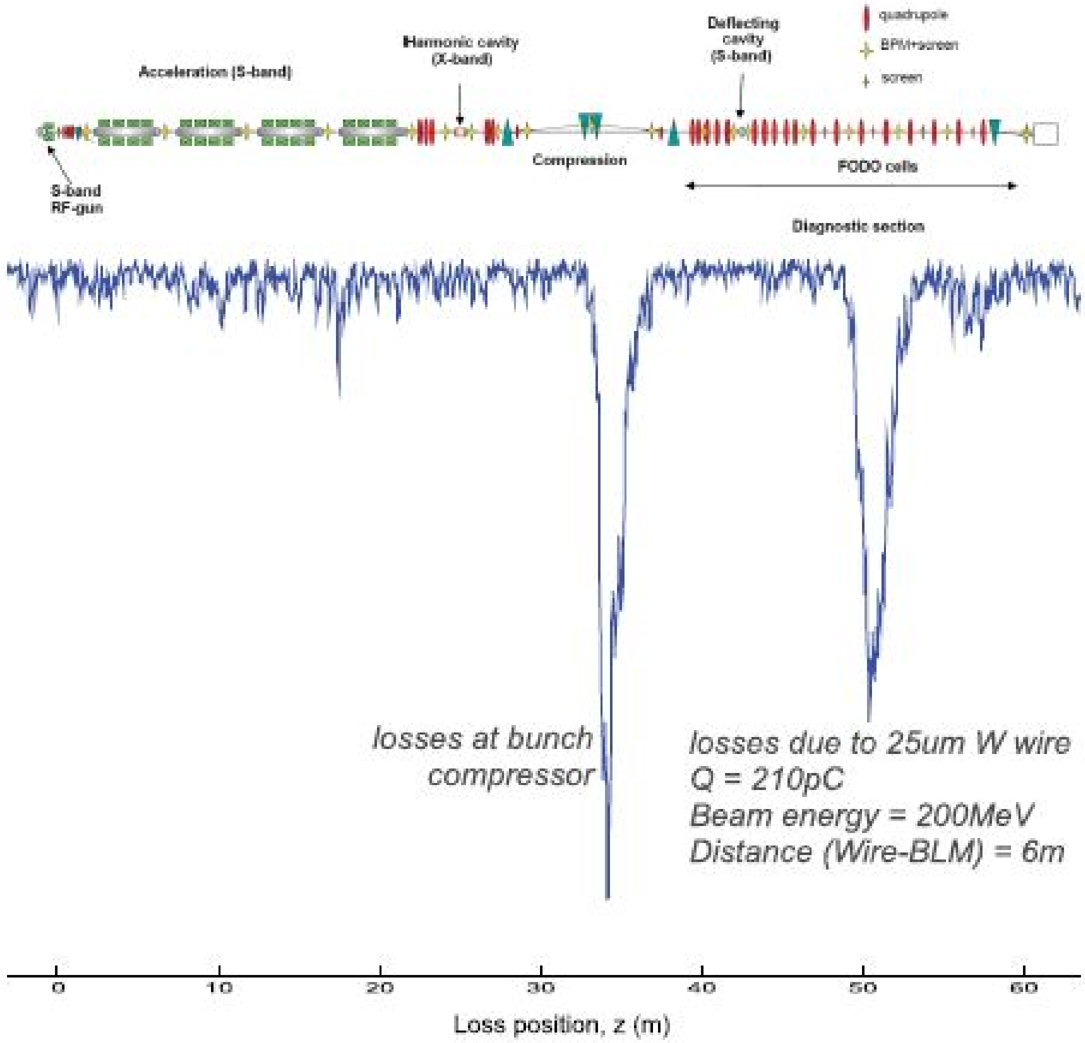


Distributed BLMs (for machine interlocks)

Based on Cherenkov radiation generated by lost particles in long optical fibers (quartz) installed along the accelerator.







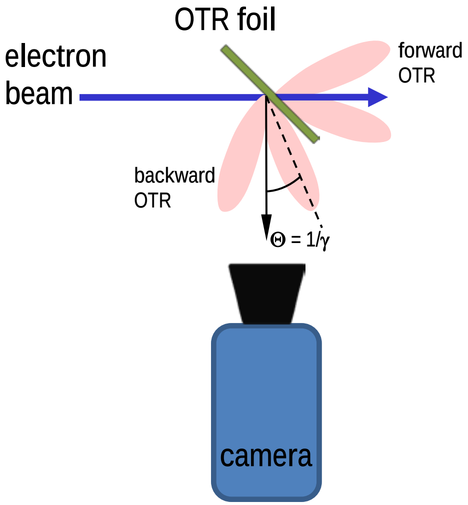
Example: beam loss distribution in SITF

Transverse Profile Imagers

- SR/DR/ER monitors
- OTR
- Scintillator Screens

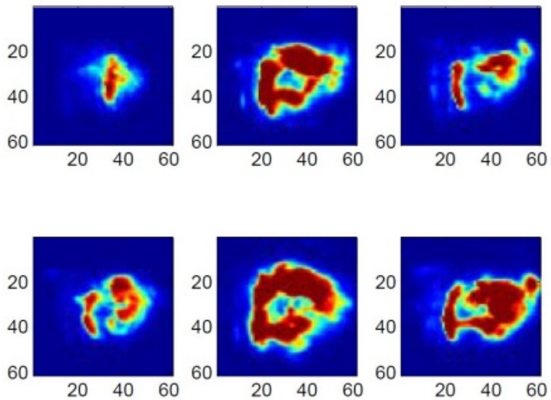
Optical Transition Radiators as 2D Transverse Profile Monitors

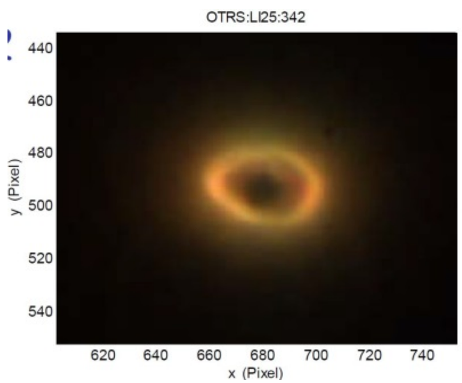
Schematic Set-Up and Main Properties of OTR as Screen Monitors



- OTR is generated when relativistic charged particles pass the boundary of two media with different dielectric (optical) properties
- OTR screen could be a thin metal foil or silicon wafer (with Al layer)
- OTR is radiated in forward and backward direction with an opening angle of $1/\gamma$
- incoherent Optical TR provides good linearity for profile measurements
- surface quality of OTR screen affects profile imaging quality (beam size)

Optical Transition Radiators as 2D Transverse Profile Monitors





Coherent OTR images from LCLS showing full saturation of camera

H. Loos, et al., *LCLS*

The PROBLEM:

Coherent OTR has been observed for highly brilliant electron beams

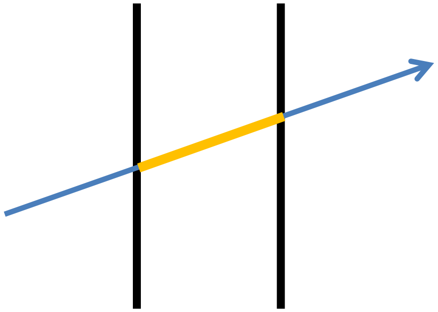
- Coherent OTR was first observed at LCLS
- SACLA and FLASH validated COTR observations

So, to measure profiles with wire scanners? but it is very slow…

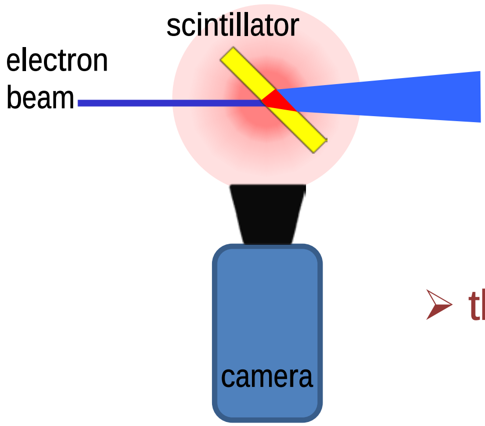
Another option – to use scintillator screens (also affected by the COTR) and try to suppress the generated COTR.

Scintillator Screens as 2D Transverse Profile Monitors
(YAG or LuAG scintillator crystals)

Schematic Set-Up and Main Properties of Scintillators as Screen Monitors

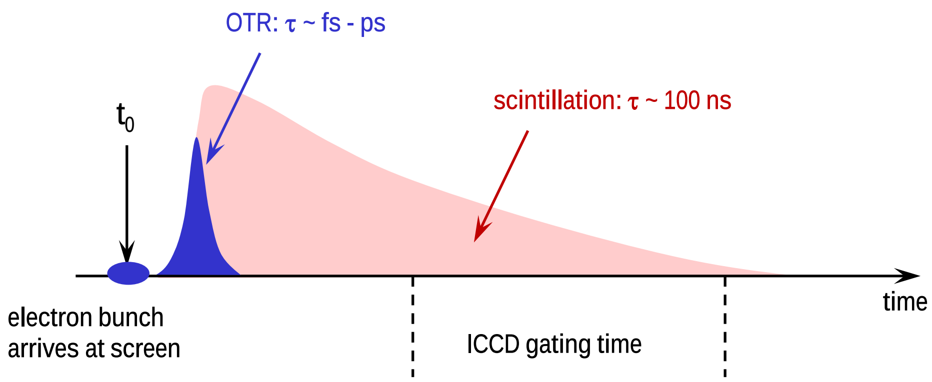


- electrons passing the scintillator crystal excite atoms and molecules, which then scintillate: re-emit the energy in the form of light
- visible light from scintillator crystals is radiated in 4π
- photons are created along the beam pass through scintillator crystal - a “light column” is formed



- scintillator crystals are very sensitive and radiation resistant
- multiple scattering in scintillator crystal increases beam divergence
- thickness of scintillator crystals and observation angles affect resolution
- COTR is formed at the border scintillator/vacuum

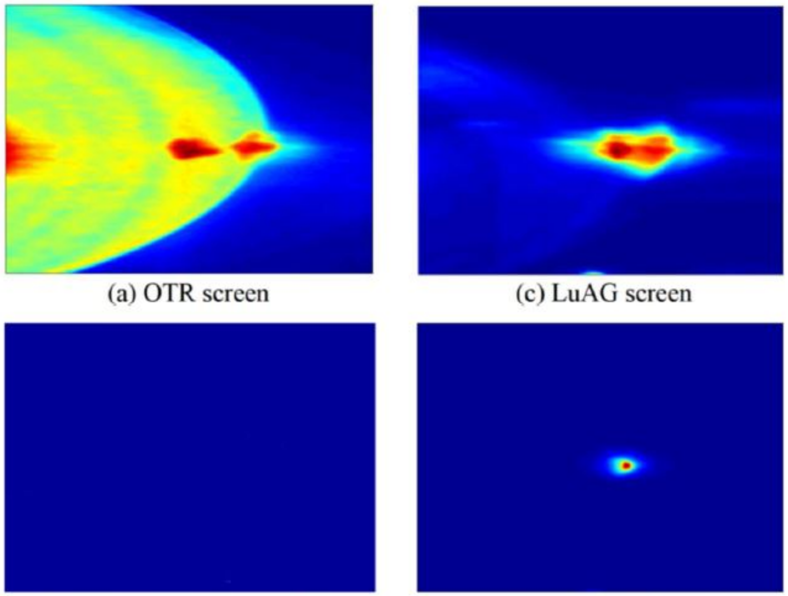
COTR Suppression: Temporal Separation with Scintillator & Gated CCD



- OTR is an instantaneous process
- Coherent OTR produces in case of micro-bunching
- Scintillation has a "long" decay time
- Scintillation is not sensitive to micro-bunching

COTR Suppression: Temporal Separation with Scintillator & Gated CCD

COTR Mitigation Tests @ FLASH using Scintillator and ICCD (Minjie Yan et al., FLASH, Hamburg)



(a) OTR screen (c) LuAG screen

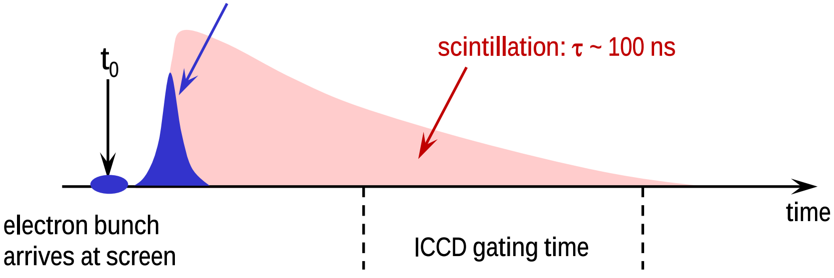
(b) OTR screen, +100ns delay (d) LuAG screen, +100ns delay

no delay at ICCD

- COTR and CSR on OTR screen
- COTR and CSR on scintillator (LuAG screen)

100 ns delay at ICCD

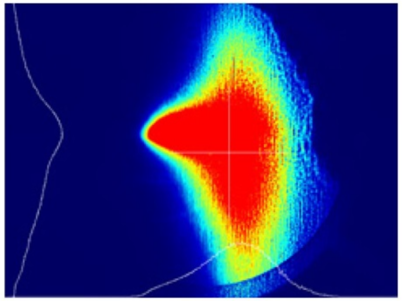
- no signal from OTR screen
- Scintillation light only from LuAG screen



COTR Suppression: Spatial Separation – Central Mask in Imaging System

- OTR is emitted at an angle $\Theta \sim 1/\gamma$
- at beam energies > 1 GeV : Θ < 0.5 mrad
- scintillation light is emitted in 4π
- central mask in imaging system successfully suppresses COTR intensity

SACLA COTR image behind BC-3



COTR Mitigation @ SACLA using Scintillator and Spatial Mask (S. Matsubara et al., Spring8, Japan)

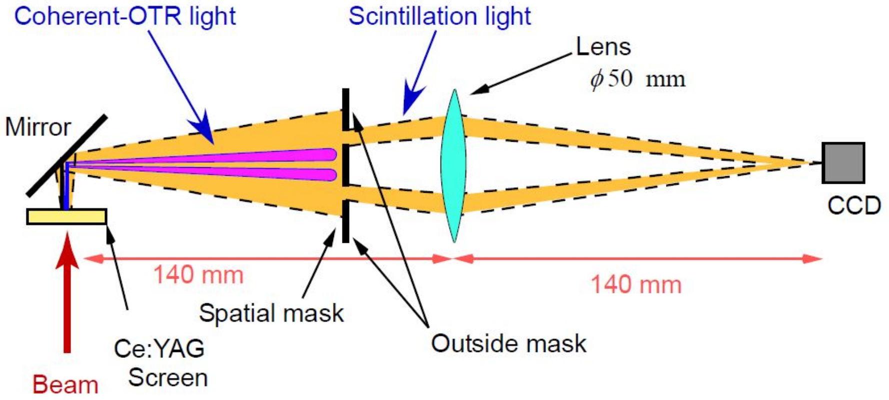
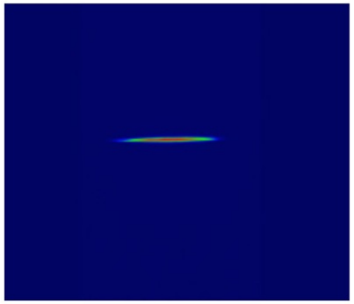
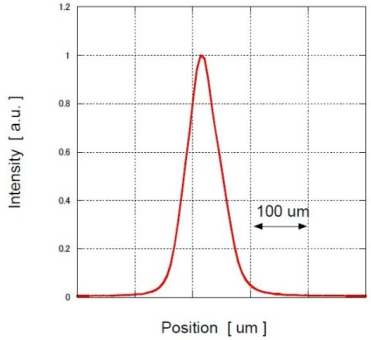


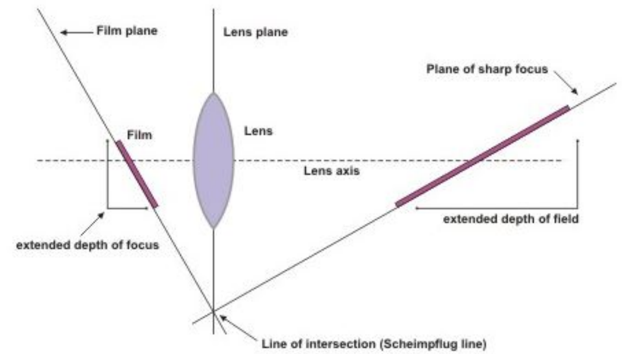
Image of vertically focused beam behind SACLA BC-3 (full compression)



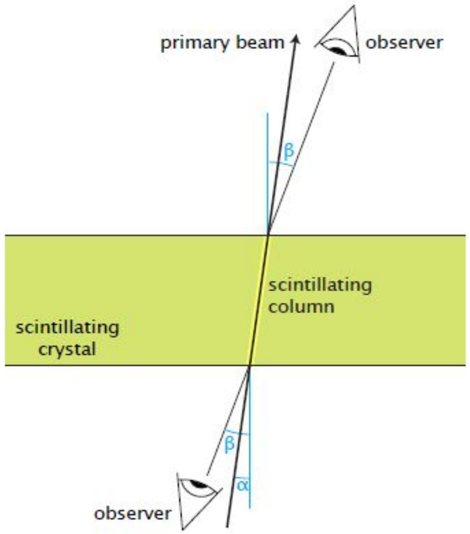


COTR Suppression: Spatial Separation – SwissFEL Profile Monitors

- 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



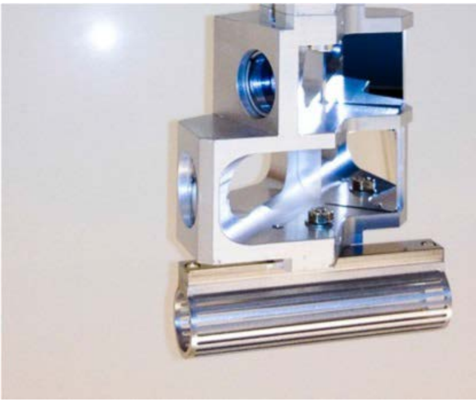
- use YAG or LuAG scintillator crystals instead of OTR
- observation of beam profile according to Snell's law of refraction
- beams can be imaged, which are smaller than scintillator thickness

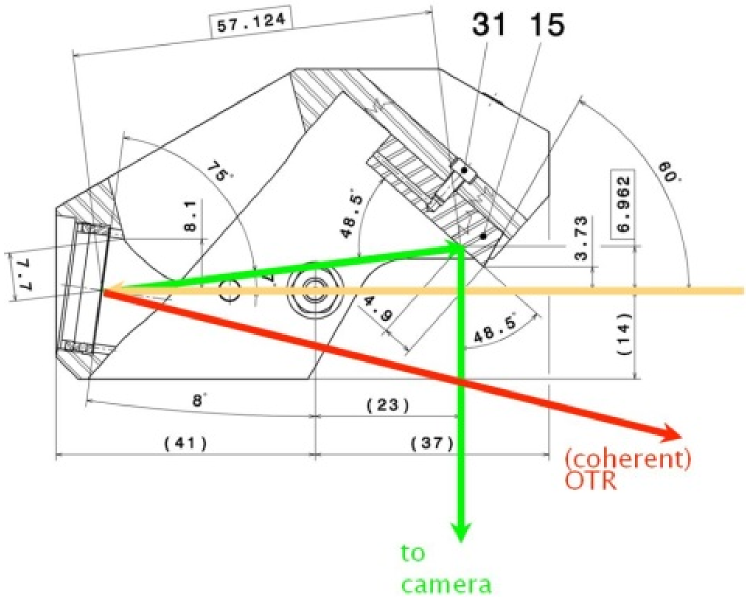


$$\frac{\sin\beta}{\sin\alpha} = n_{scint}$$

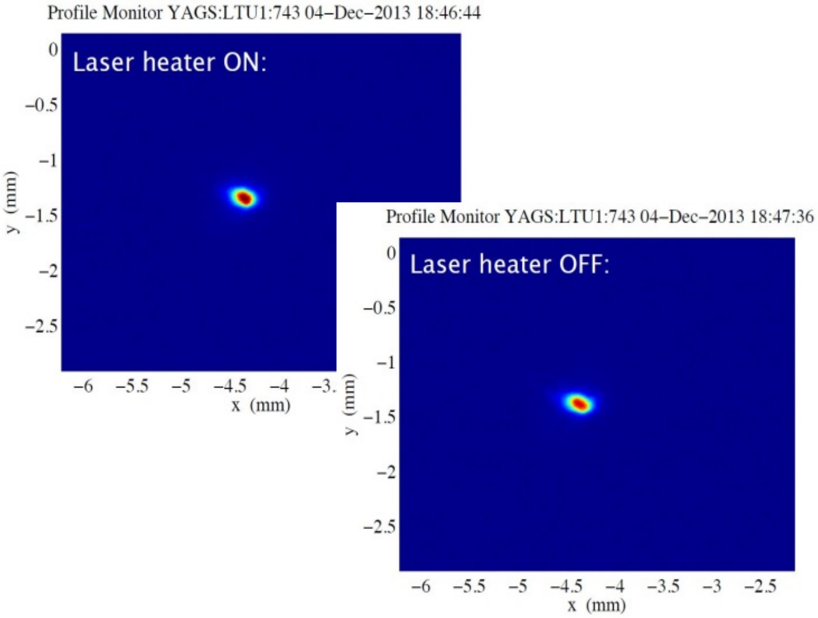
COTR Suppression: Spatial Separation – SwissFEL Profile Monitors

COTR Mitigation for SwissFEL Screen Monitors



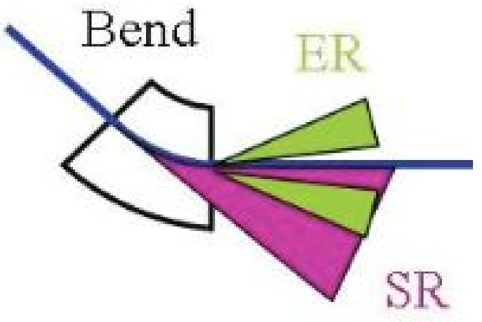


COTR suppression tests at LCLS (full compression, 20 pC)



Bunch Compression Monitor

Coherent Radiation Based Diagnostics



Bunch radiation spectrum

$$\frac{\mathrm{d}U}{\mathrm{d}\lambda} = \left(\frac{\mathrm{d}U}{\mathrm{d}\lambda}\right)_0 \left(N + N(N-1)\,|F(\lambda)|^2\right)$$

where

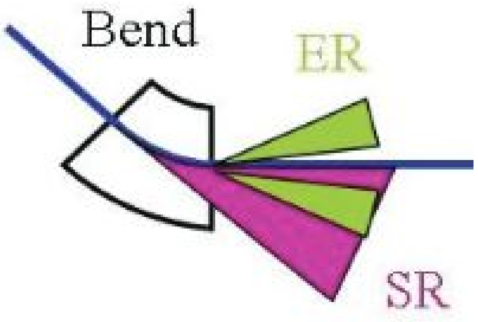
$(\mathrm{d}U/\mathrm{d}\lambda)_0$

is emission spectrum of one electron
and

$$F(\lambda) = \int_{-\infty}^{\infty} S(z) \exp\left(\frac{-2\pi \mathrm{i}}{\lambda} z\right) \mathrm{d}z$$

is the bunch form factor

Coherent Radiation Based Diagnostics



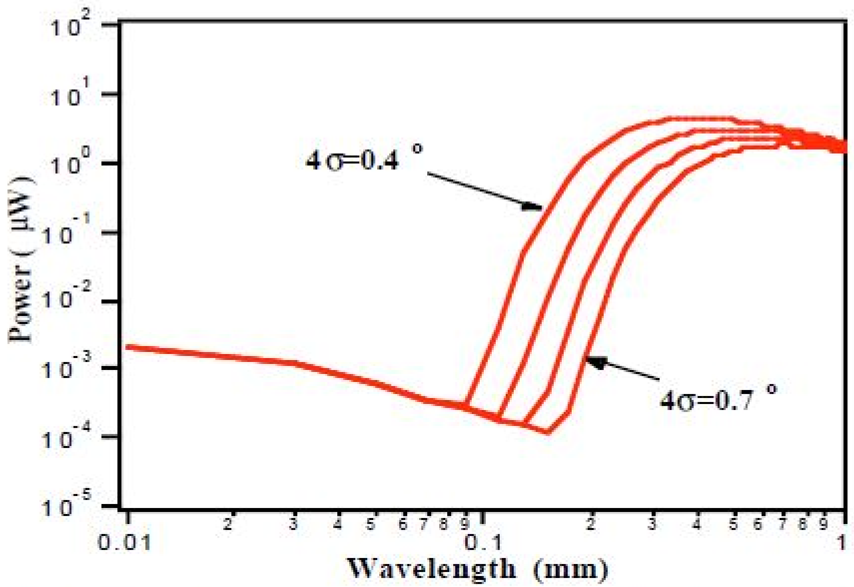


Fig. 1 Plot of Power vs. Wavelength for Injector CSR Port

Bunch radiation spectrum

$$\frac{\mathrm{d}U}{\mathrm{d}\lambda} = \left(\frac{\mathrm{d}U}{\mathrm{d}\lambda}\right)_0 \left(N + N(N-1)\,|F(\lambda)|^2\right)$$

where

$(\mathrm{d}U/\mathrm{d}\lambda)_0$

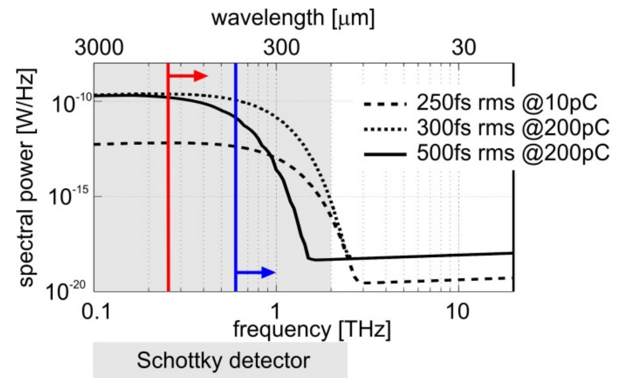
is emission spectrum of one electron and

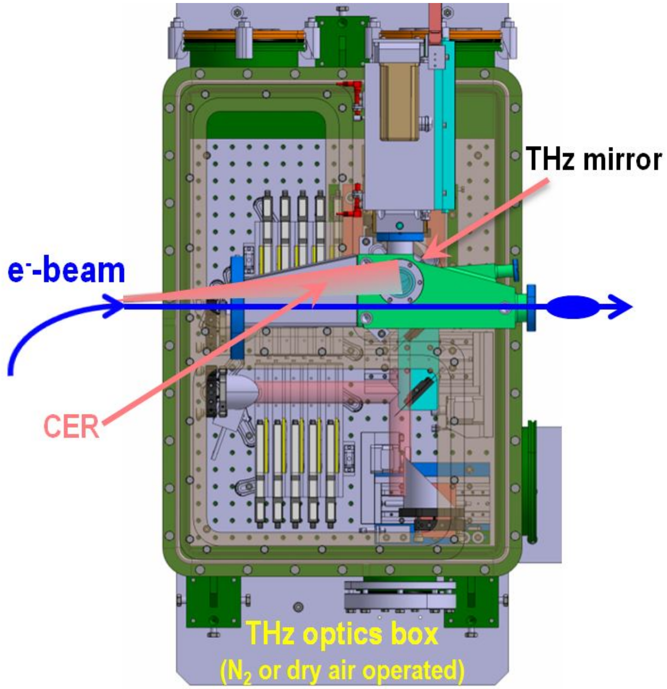
$$F(\lambda) = \int_{-\infty}^{\infty} S(z) \exp\left(\frac{-2\pi \mathrm{i}}{\lambda} z\right) \mathrm{d}z$$ is the bunch form factor

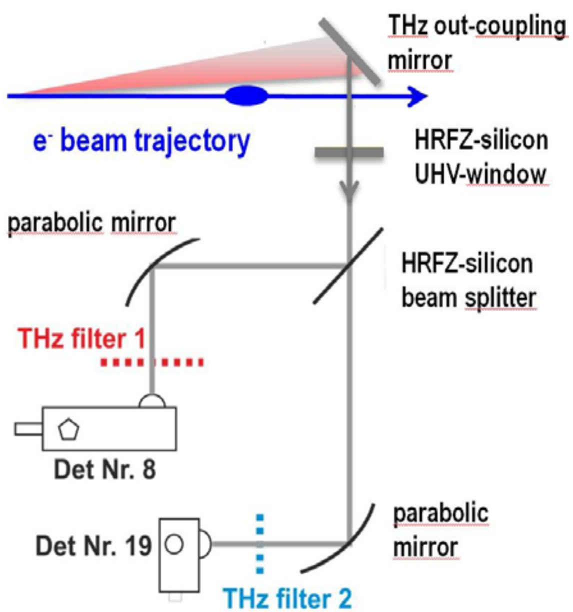
SwissFEL BC-1 THz Compression Monitor

- 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

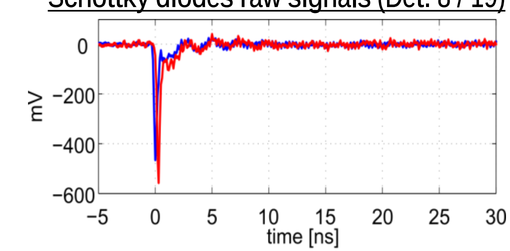
spectral range of CER and THz filters for BC-1







Schottky diodes raw signals (Det. 8 / 19)



SwissFEL BC-1 THz Compression Monitor

- 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

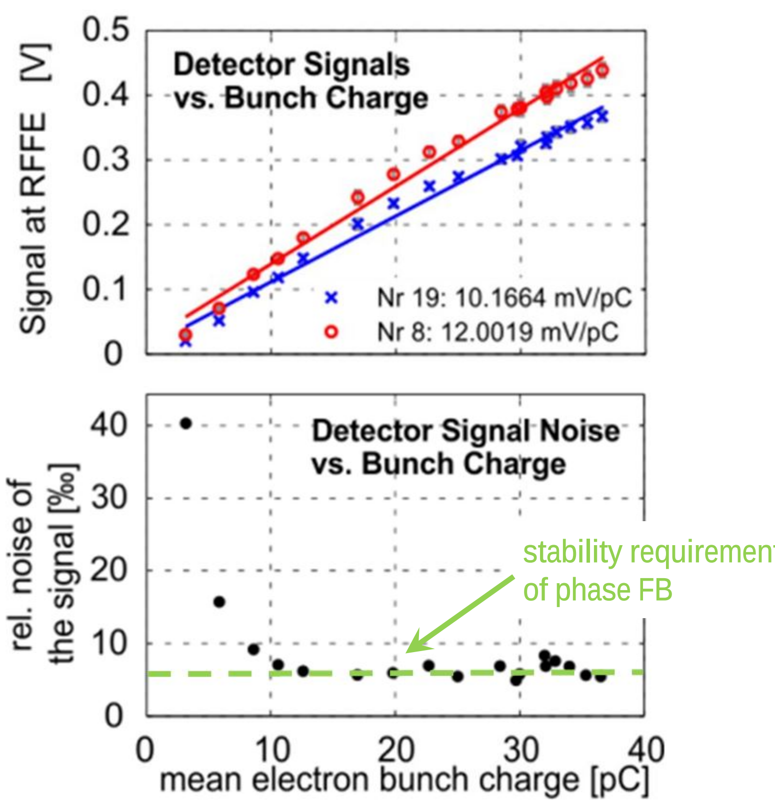


Table 1 - Commercially Available Room Temperature THz Detectors

	NEP $W/Hz^{1/2}$	Responsivity V/W	Response Time (seconds)	Operating Temp (K)
Golay cells [3]	10^{-10}	10^{5}	10^{-2}	300
Pyroelectrics [4]	10^{-10}	10^{5}	10^{-2}	240-350
Schottky diodes [5]	10^{-12}	10^{3}	10^{-12}	10-420

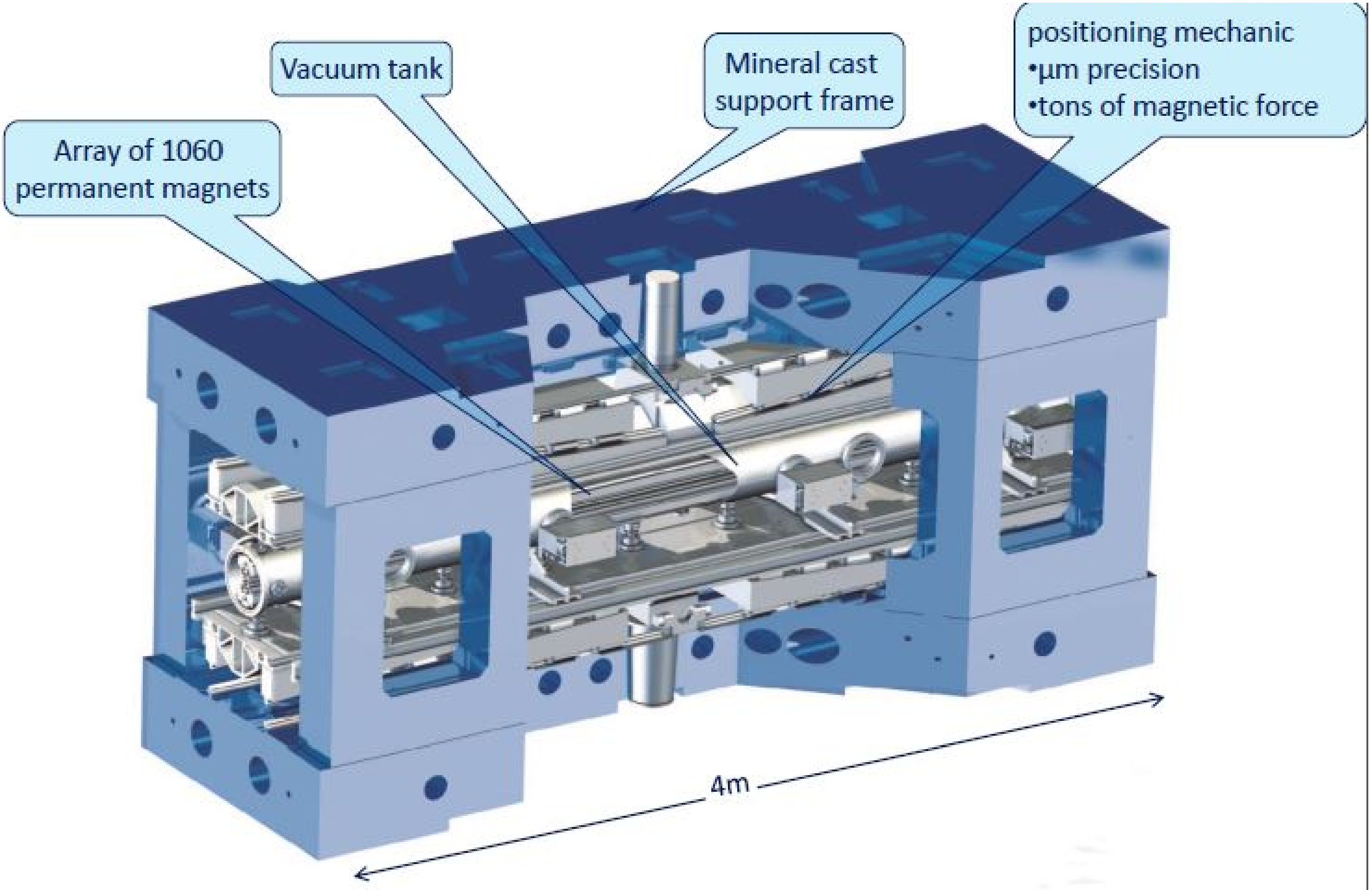
Summary

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 Undulators
→ 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-2 (~ 4 % absolute) 145 x BPMs (0.1% relative)
→ Beam Loss Monitors:	38 scintillating monitors (high sensitivity) 8 distributed Cherenkov 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 undulators)
→ 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)

References

V. Schlott, R. Ischebeck, S. Reiche, B. Keil, B. Steffen,
V. Arsov, P. Peier, F. Muller, F. Frei, S. Hunziker,
B. Beutner, M. Kaiser, C. Ozkan, F. Lohl

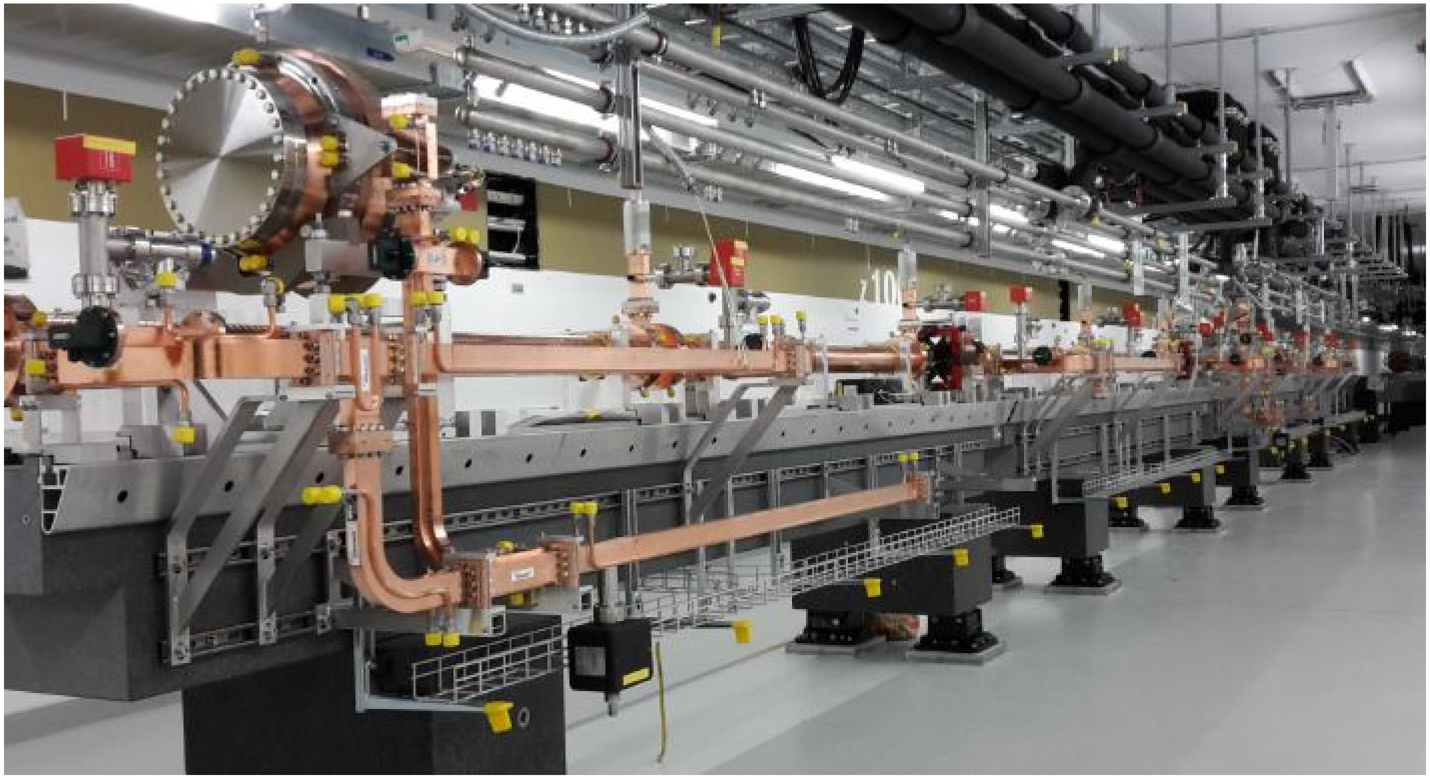


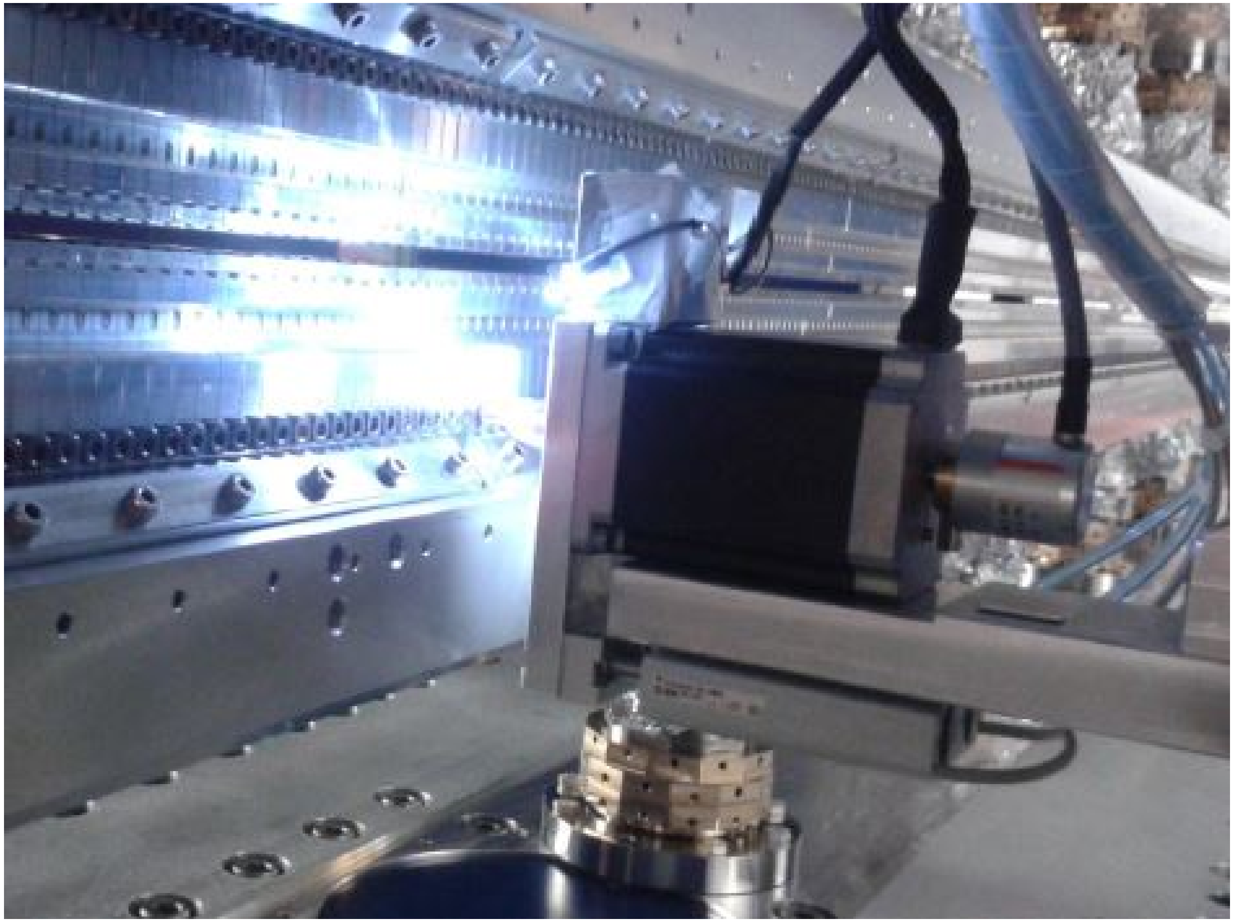
Vacuum tank
Mineral cast support frame
positioning mechanic
•µm precision
•tons of magnetic force
Array of 1060 permanent magnets
4m

U15 parameters

Type	Hybrid - In Vacuum				
# units	12				
Period	15				mm
# periods	266 (including ends)				
Magnetic length	3990				mm
K-values	1.8	1.4	1.2	1.0	-
GAP	3.2*	4.2	4.7	5.5	mm
Bz max	1.27	1	0.85	0.7	T
Br	1.25				T
Hc_J	>2400				kA/m
Magnet size	WxHxT=30x20x2.25				mm
Pole size	Wb/WtxHxT=20/15x16.5x3				mm
Max GAP	20.0				mm
ΔGAP	0.3				μm

*Minimum magnetic GAP (Vacuum GAP=3mm)





Robot adjusting magnet positions in the SwissFEL undulator


Thank you!