Large Swiss Particle Accelerator Facilities and their Basic Beam Diagnostics Tools

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Outlook

- Introduction/ Swiss National Research Center (Paul Scherrer Institute, PSI)

- PSI Accelerator Facilities and their Basic Beam Diagnostics

  - SwissFEL (with some commissioning experience)
  - Swiss Light Source
  - High Intensity Proton Accelerator complex

- Summary/Conclusions

2012: ~ **30’000 accelerators** operational world-wide*

The **large majority** is used in **industry** and **medicine**

- Industrial applications: ~ 20’000*
- Medical applications: ~ 10’000*

Less than a fraction of a percent is used for **research** and discovery science

- Cyclotrons
- FFAG
- Synchrotrons
- Synchrotron light sources (e^-)
- Lin. & Circ. accelerators/Colliders

*Source: *World Scientific Reviews of Accelerator Science and Technology* *A.W. Chao*

Large Research Accelerator Facilities in Switzerland

CERN, Geneva


SwissFEL
SLS
HIPA

Paul Scherrer Institute (PSI), Villigen, near Zurich

1960 Eidgenössisches Institut für Reaktorforschung (EIR)

1968 Schweizer Institut für Nuklearphysik (SIN)

1988 EIR + SIN = PSI ⇨ research with photons, neutrons, muons

Paul Scherrer Institute (PSI)

PSI Accelerators:

- 590 MeV proton cyclotron: 1.3 MW beam power
  ⇨ spallation neutron source SINQ & muon source SμS
- 2.4 GeV synchrotron light source SLS
- 5.8 GeV / 1 Å free electron laser SwissFEL

Paul Scherrer Institute (PSI)

- Annual budget ~ 300 MCHF
- 2000 employees (27% women, 49% non-Swiss citizens)

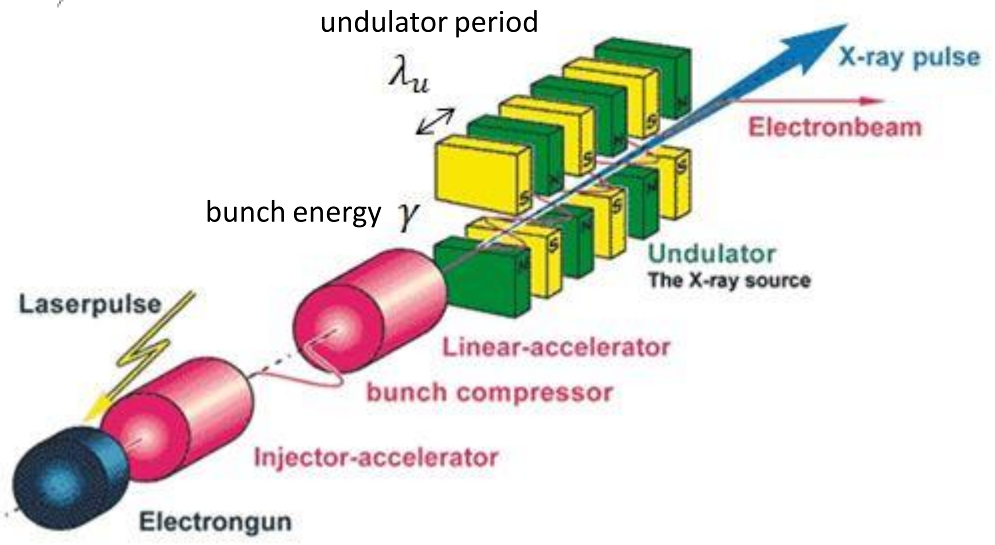
Swiss Free Electron Laser (SwissFEL) Facility

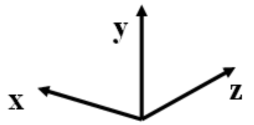
SwissFEL – a hard X-ray (0.1 nm) SASE* FEL

SASE* (Self Amplified Spontaneous Emission) FEL

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

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

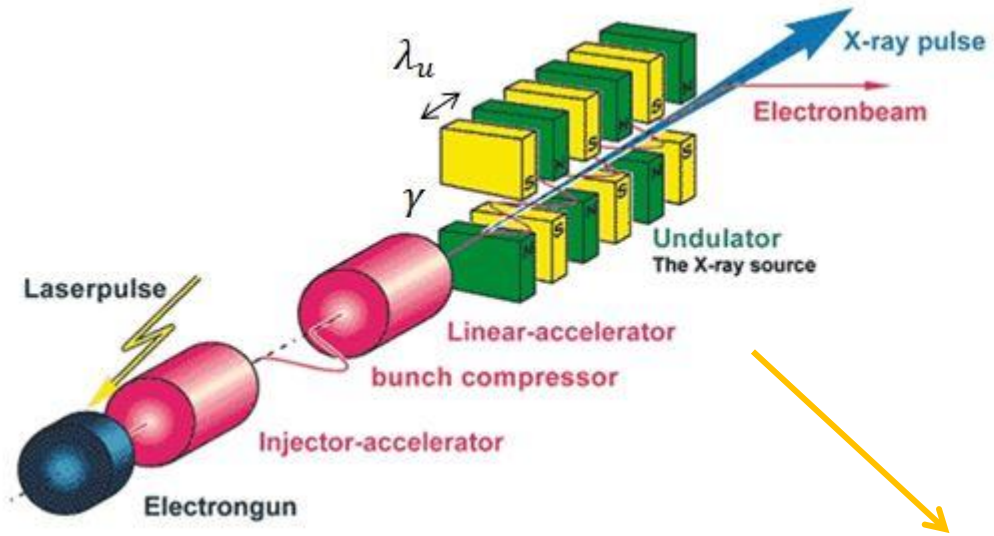




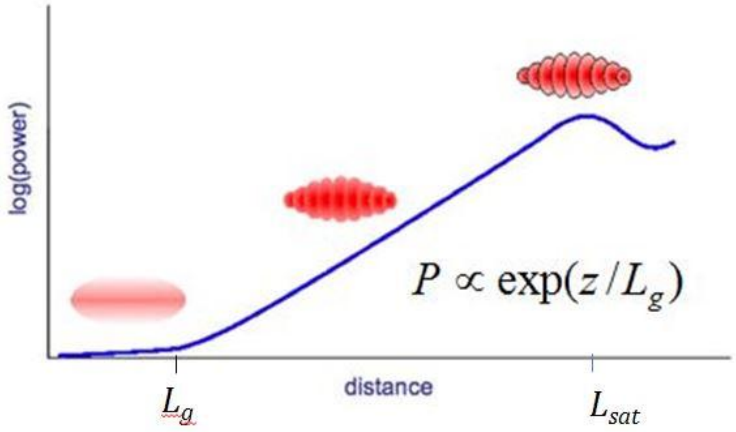
- relativistic electron bunch
- a (long enough) undulator

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

SASE (Self Amplified Spontaneous Emission) FEL



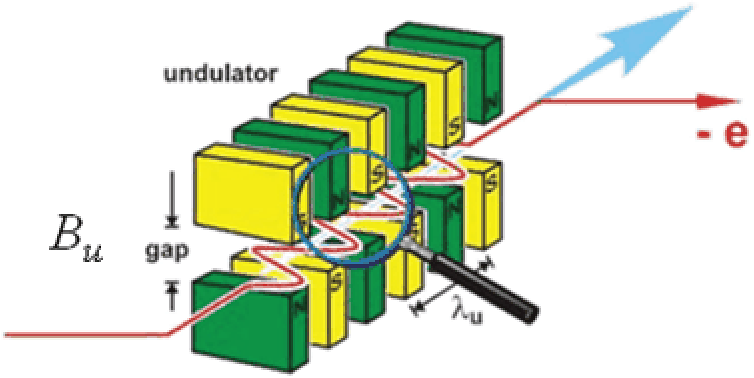
- In the undulator, the bunch is modulated by its own synchrotron radiation field
- Electrons are “self-organized” in micro-bunches, which radiate coherently
- The total radiated power grows exponentially until it reaches saturation

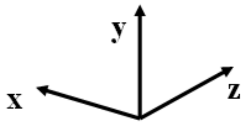


SASE FEL performance conditions

- **A resonance condition in the undulator**

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





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

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

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

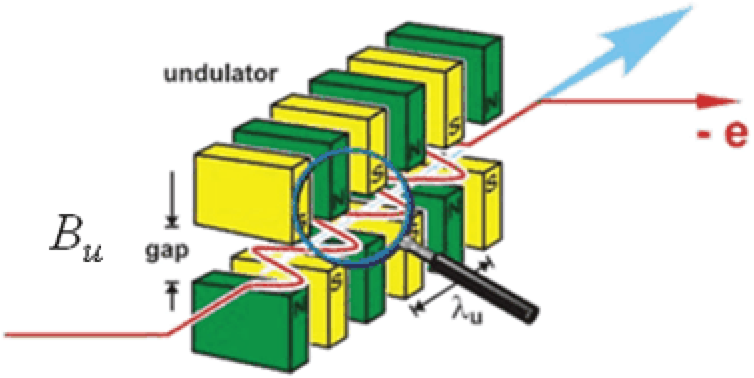
$$K = \frac{eB_u\lambda_u}{2\pi mc} \approx 0.93\ \lambda_u\ [\mathrm{cm}]\ B_u\ [\mathrm{T}]$$

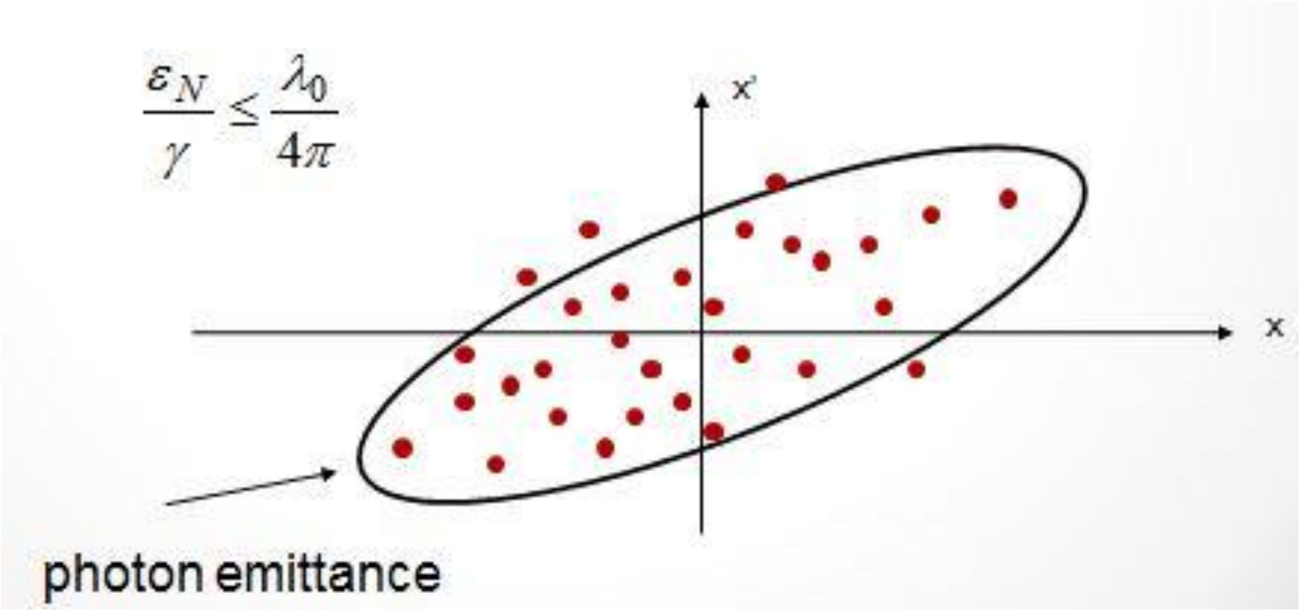
undulator parameter

Parameters for lasing at 1 Å

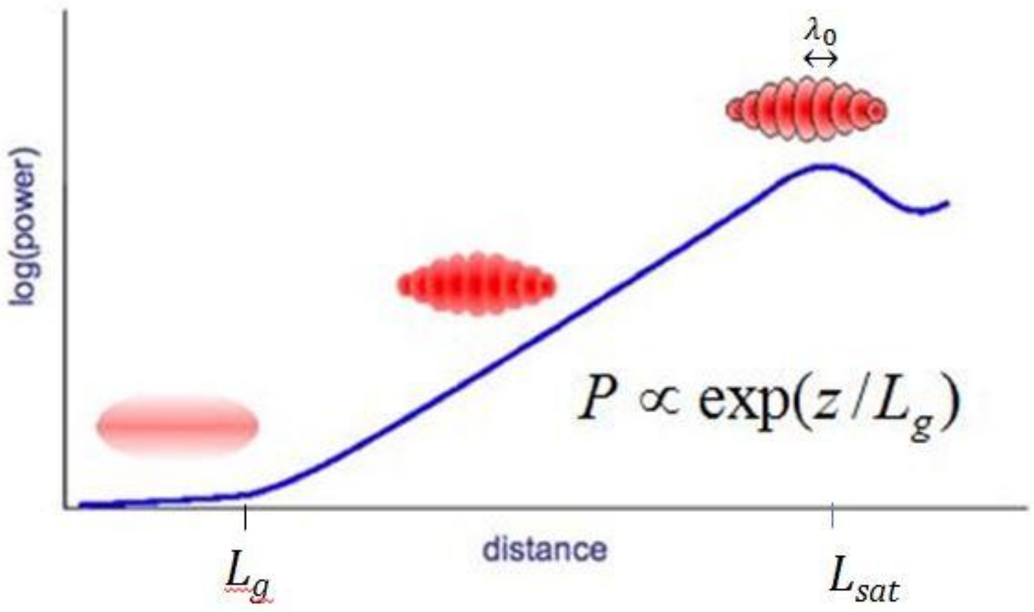
Beam energy	5.8 GeV
λ_U	15 mm
K	1.2

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





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



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

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

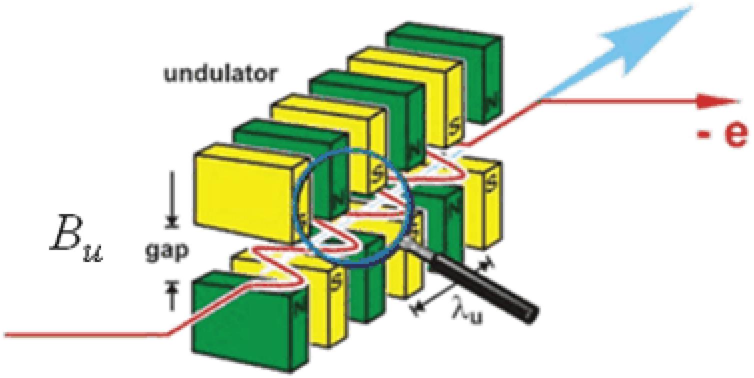
FEL parameter

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

$L_{sat} \sim 1/\rho$

SwissFEL (0.1 nm) - 45 m

So, SASE FEL requires



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

SwissFEL Highlights

Some 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/mm^2/mrad^2/0.1% 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	2856	2998.8 ($21xf_b$)
	X-Band (4 x S-band)	11991.648	11424	11995.2 ($84xf_b$)
Main linac	C-Band (2 x S-band)	5998.524	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

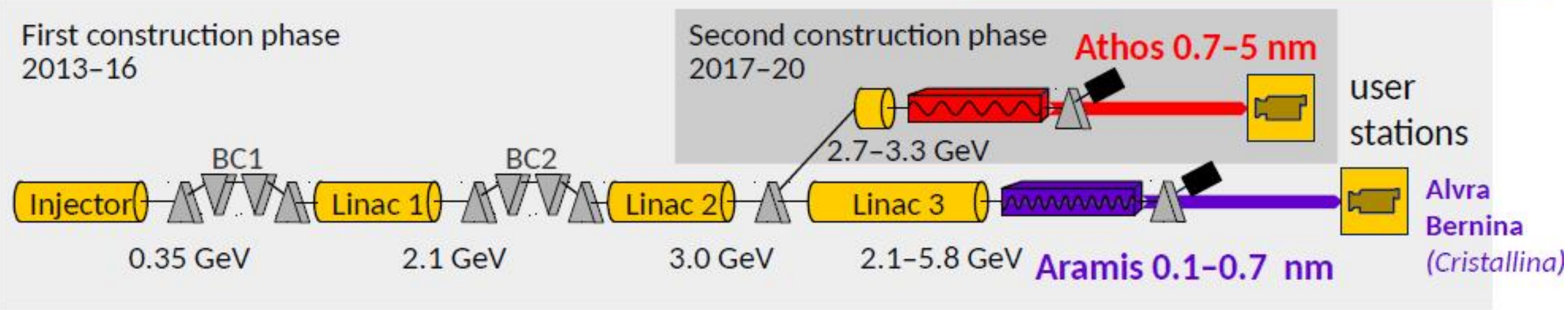
SwissFEL Overview

Athos:

Soft X-ray FEL, λ=0.65–5.0 nm

Variable polarization, Apple-X undulators

First users 2021



Aramis:

Hard X-ray FEL, λ=0.1–0.7 nm

Linear polarization, variable gap, in-vacuum undulators

First users 2018

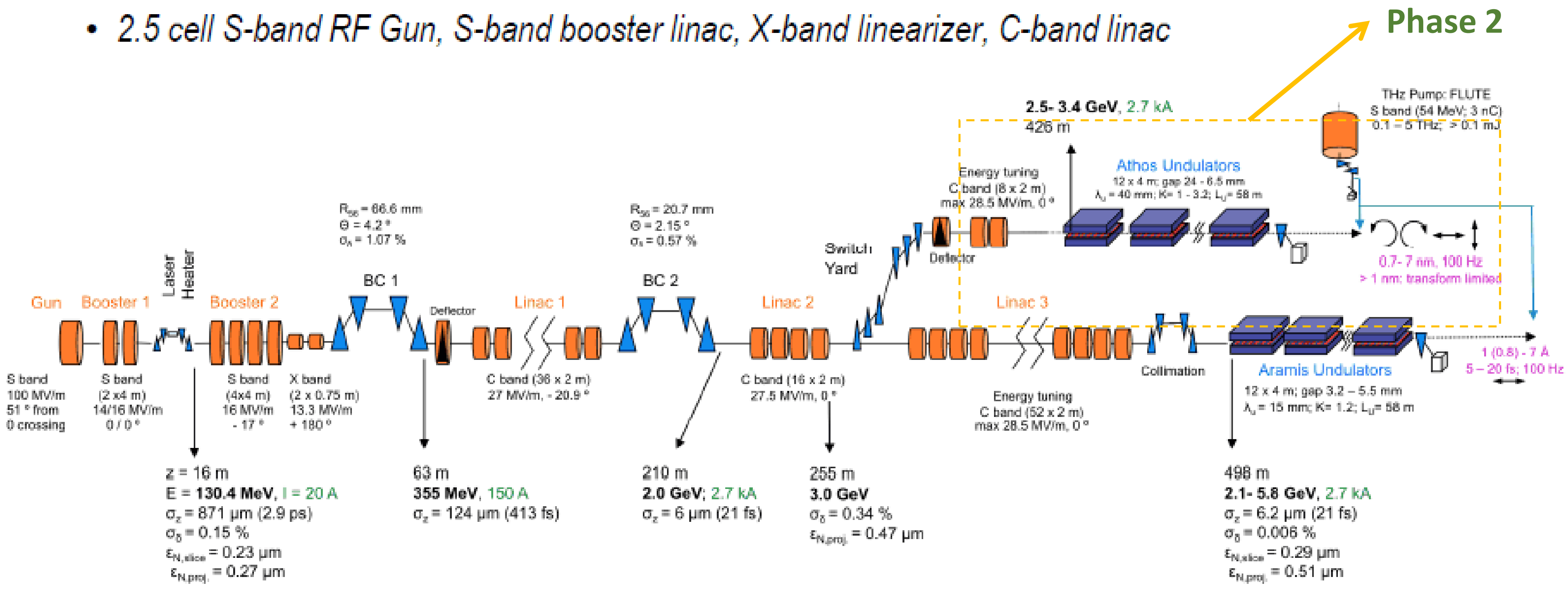
Main parameters:

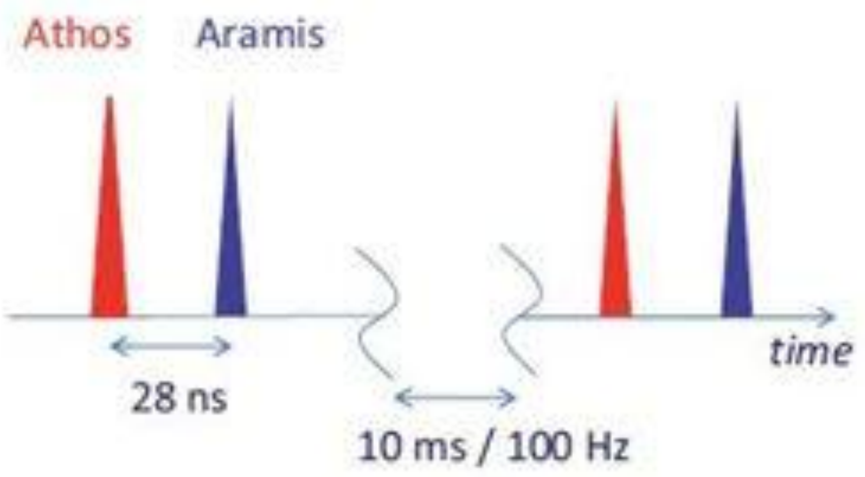
Photon wavelength	0.1–5 nm
Photon energy	0.2–12 keV
Pulse duration	1–20 fs
Electron energy	5.8 GeV
Electron bunch charge	10–200 pC
Repetition rate	100 Hz

- ***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

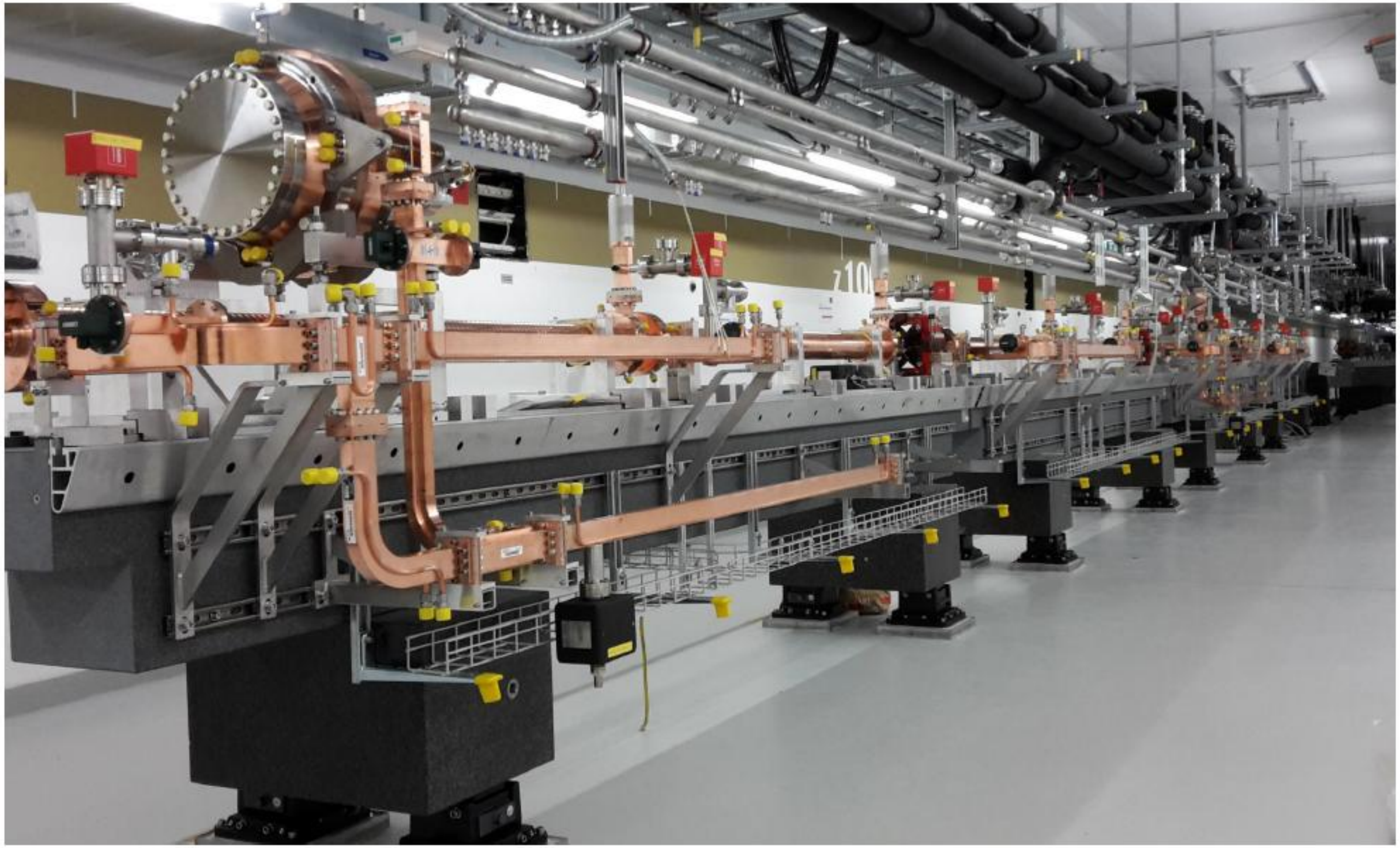
- ***RF:***
  - *2.5 cell S-band RF Gun, S-band booster linac, X-band linearizer, C-band linac*





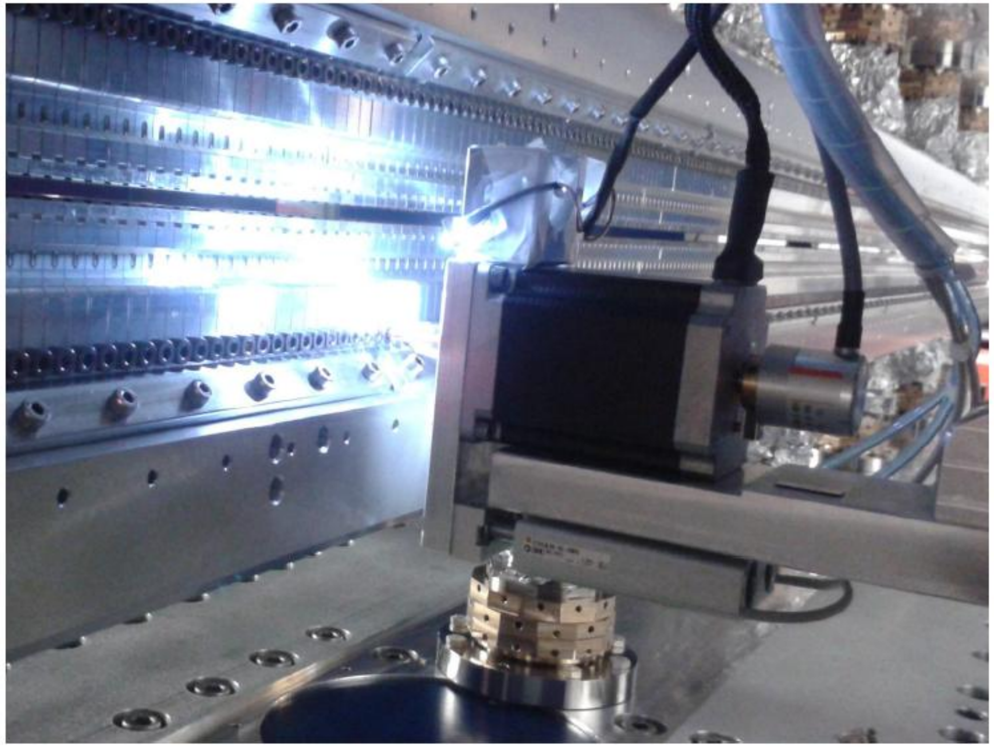
SwissFEL two-bunch operation

C-Band Linac Modules in SwissFEL Tunnel

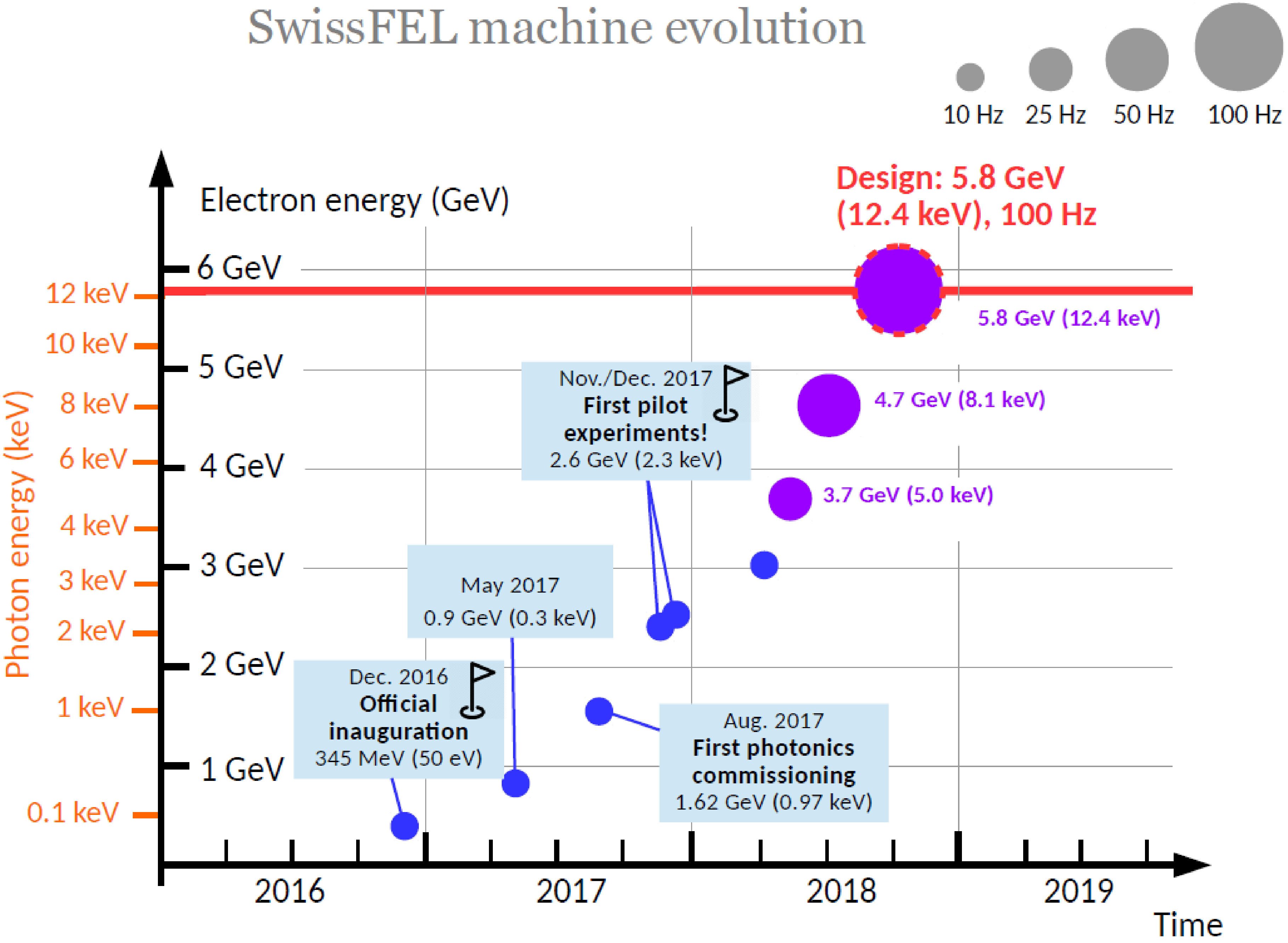


SwissFEL Undulators

Robot adjusting positions of magnets

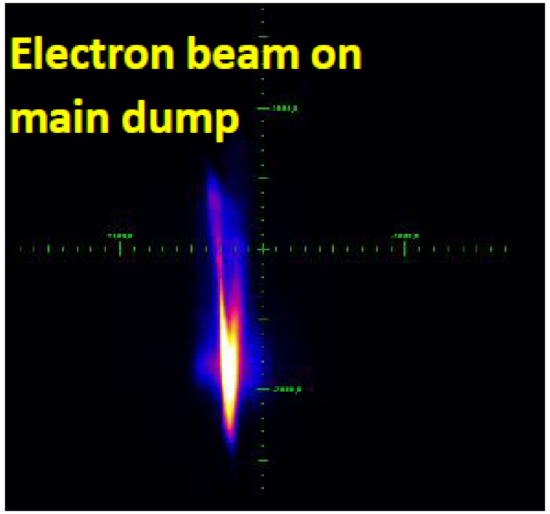


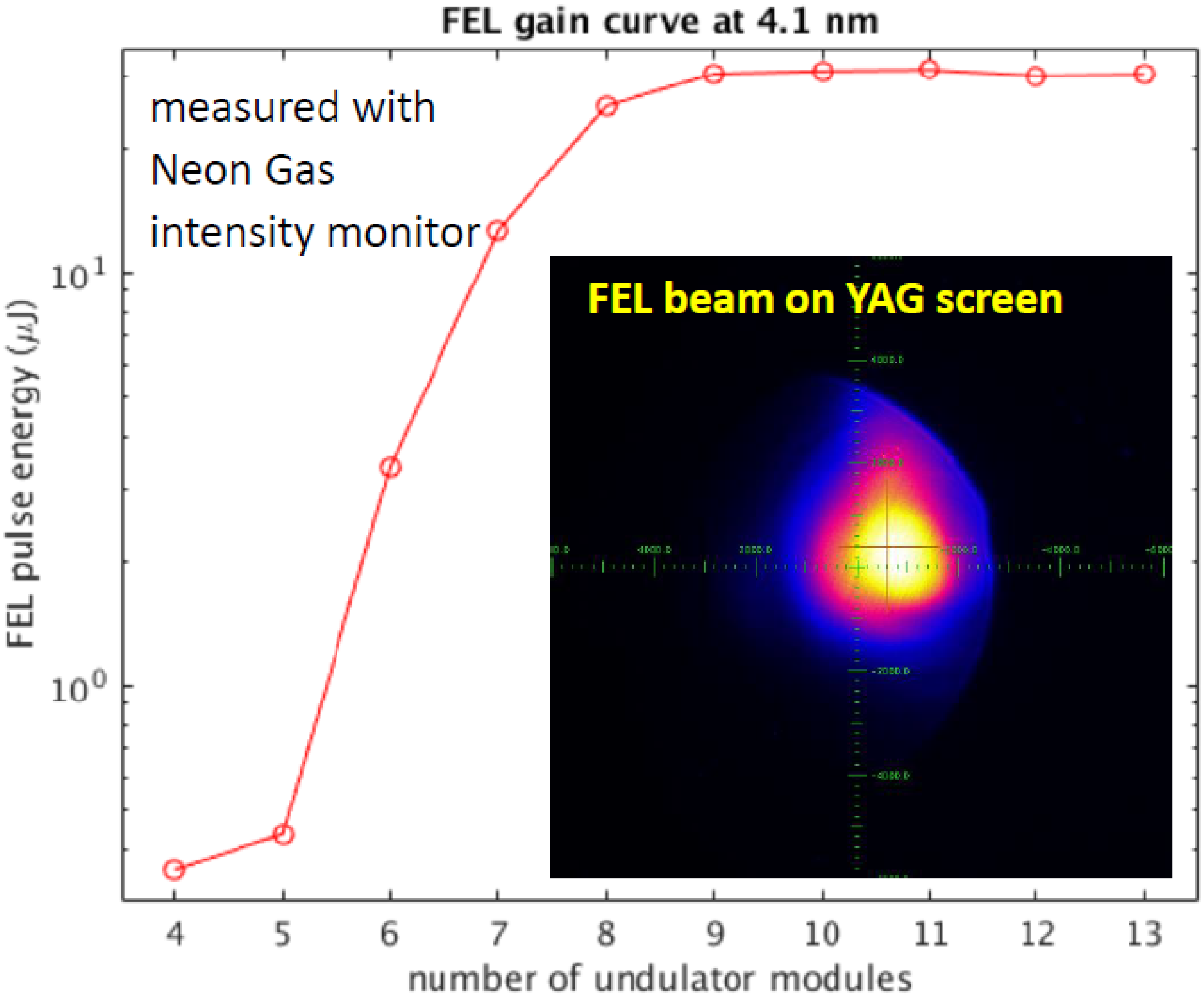
SwissFEL machine evolution



First lasing in nominal SwissFEL wavelength range (0.1-5.0 nm)

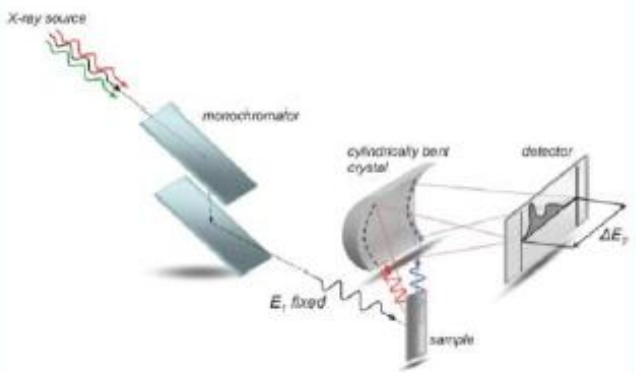
E_{e^-}	0.91	GeV
q_B	145	pC
b.l. (rms)	≈0.4	ps
K	1.2	
λ_{FEL}	4.1	nm
W_{FEL}	≈30	µJ





SwissFEL Aramis experimental stations

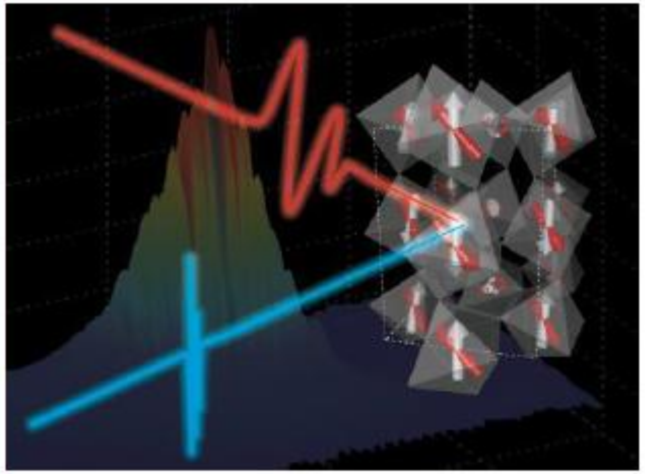
ESA:
Ultrafast photochemistry and photobiology



- XAS & XES
- WAXS & SAXS
- SFX

- liquid samples

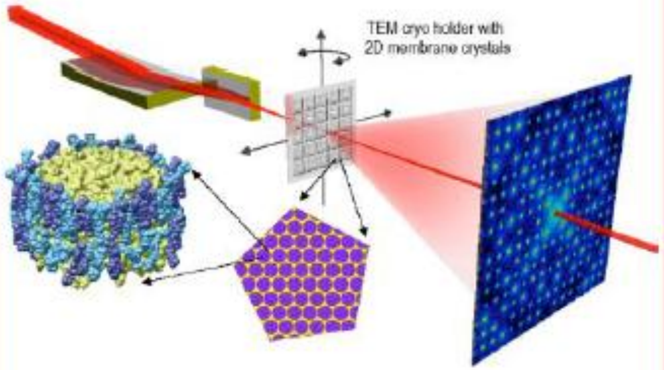
ESB:
Ultrafast dynamics in solid matter, strongly correlated electron systems



- (resonant) x-ray diffraction
- x-ray scattering: diffuse, inelastic …

- Solid matter

ESC:
Coherent diffraction and nanocrystallography



SwissFEL Machine/Beam Diagnostics
(+ commissioning facts)

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)

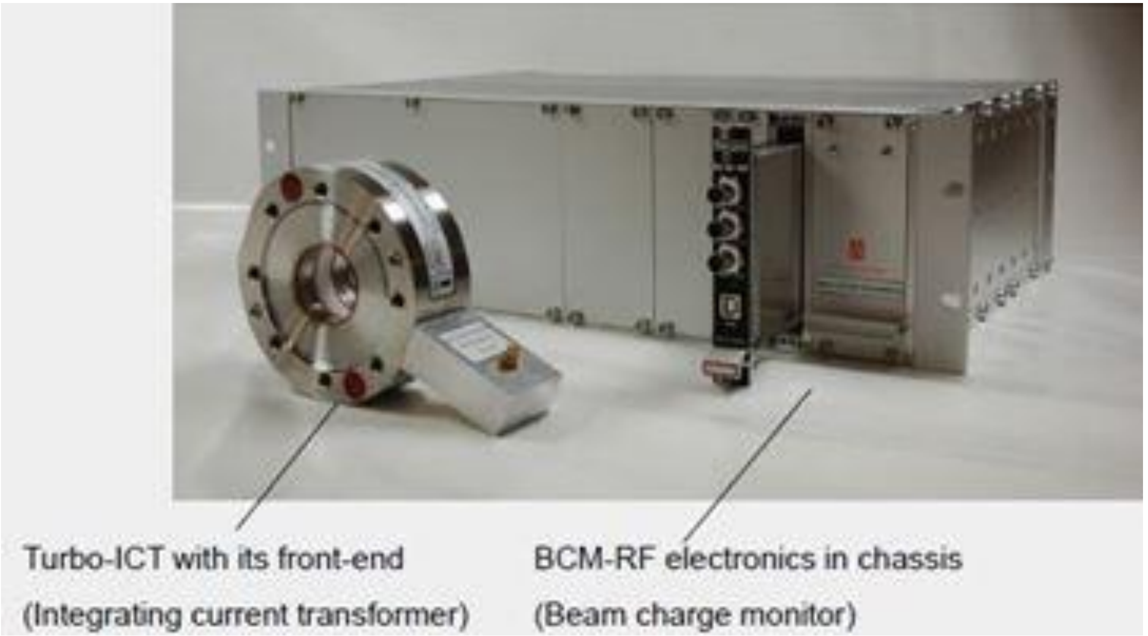
SwissFEL Key Parameters	Operation Modes	
	Long Bunch	Short Bunch
Bunch Length	20 fs (rms)	2.5 fs (rms)
Comp. Factors	125	240
Norm. $\varepsilon_{h,v}$	430 nmrad	180 nmrad
Timing Stability	Jitter	Drift
Sync. System	< 10 fs	< 20 fs / day
Bunch Arrival	< 10 fs	< 10 fs / day

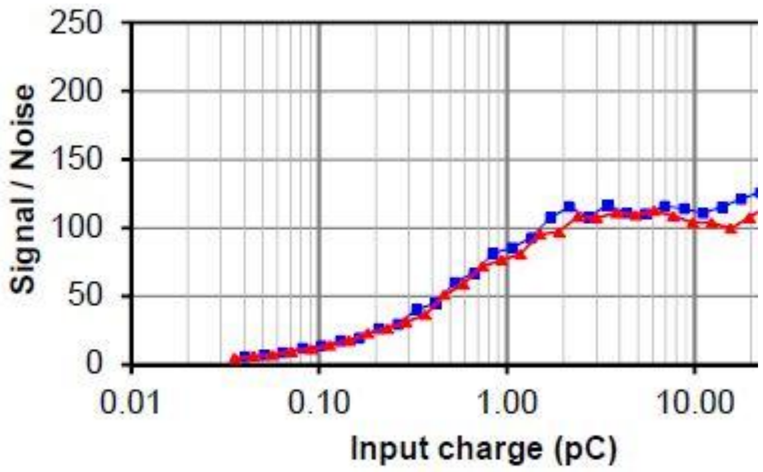
Beam Charge Monitors

Main SwissFEL requirements:

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

Bergoz Turbo-ICT





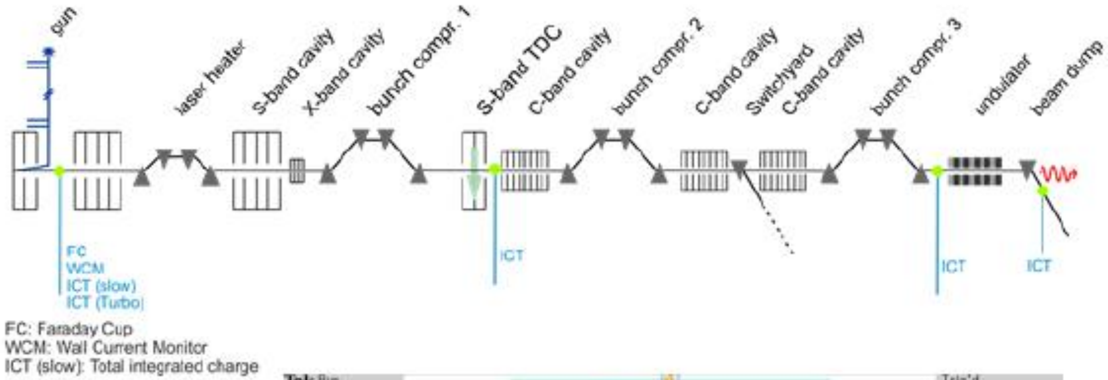
blue squares – first bunch
red squares – second bunch

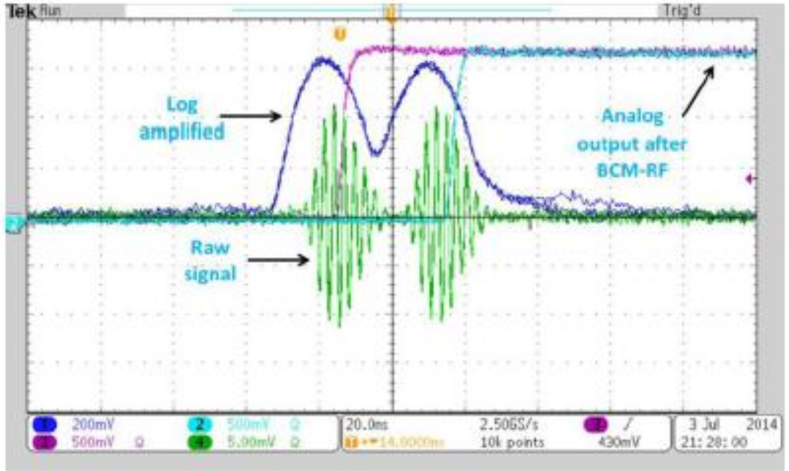
- **Delivered as a fully calibrated device**
- **Not sensitive to the dark current due to its fast readout of the beam induced current (3 ns) at higher bandwidth**

Commissioning Experience – Turbo-ICTs

Beam Charge Monitors – Turbo ICTs / BCM-RF

- 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)
- ICTs are integrated in SwissFEL Machine Protection System and used for charge calibration of BPMs





BPM

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:

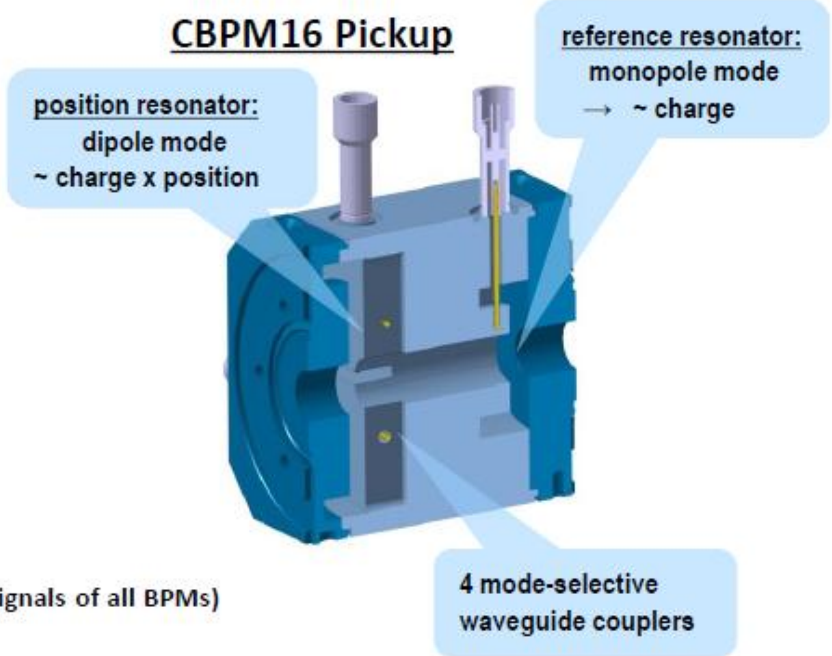
- Based on E-XFEL electronics (PSI, Swiss in-kind contribution to the European project).
  Small modifications are made to meet SwissFEL specs.

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

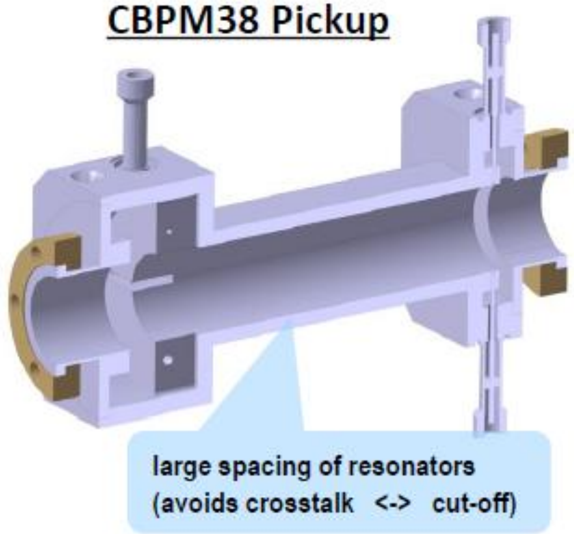


CBPM38 Pickup

CBPM16 Pickup

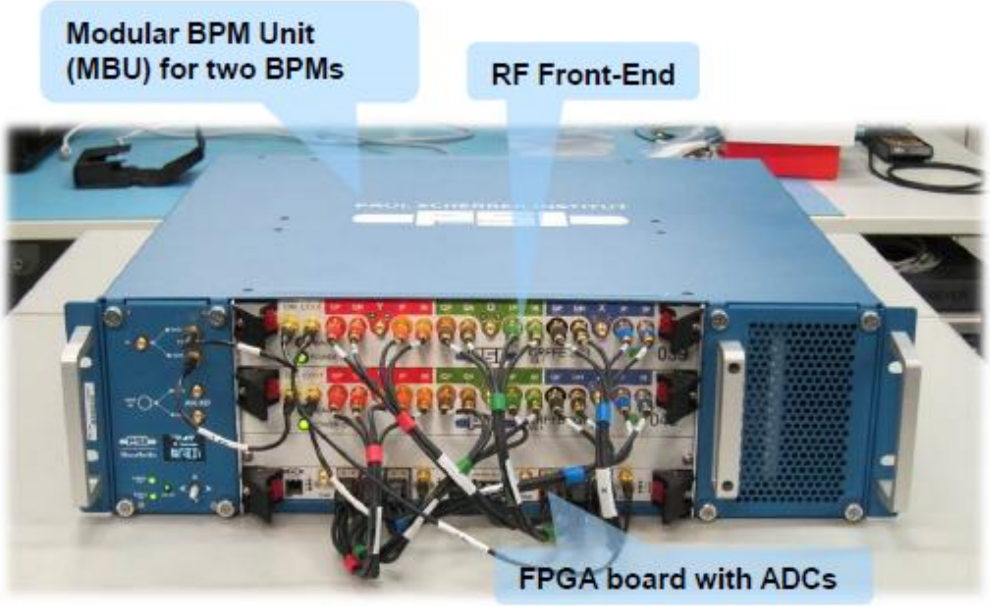
CBPM8 Pickup

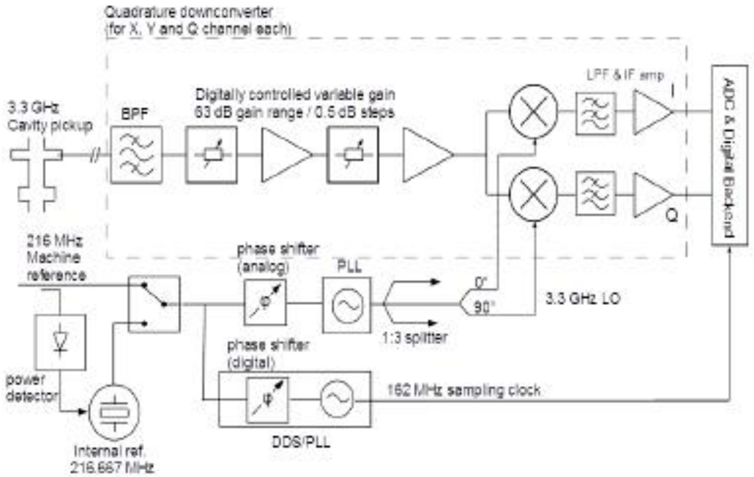
CBPM38 Pickup



Commissioning Experience - BPMs

SwissFEL Cavity BPM Electronics

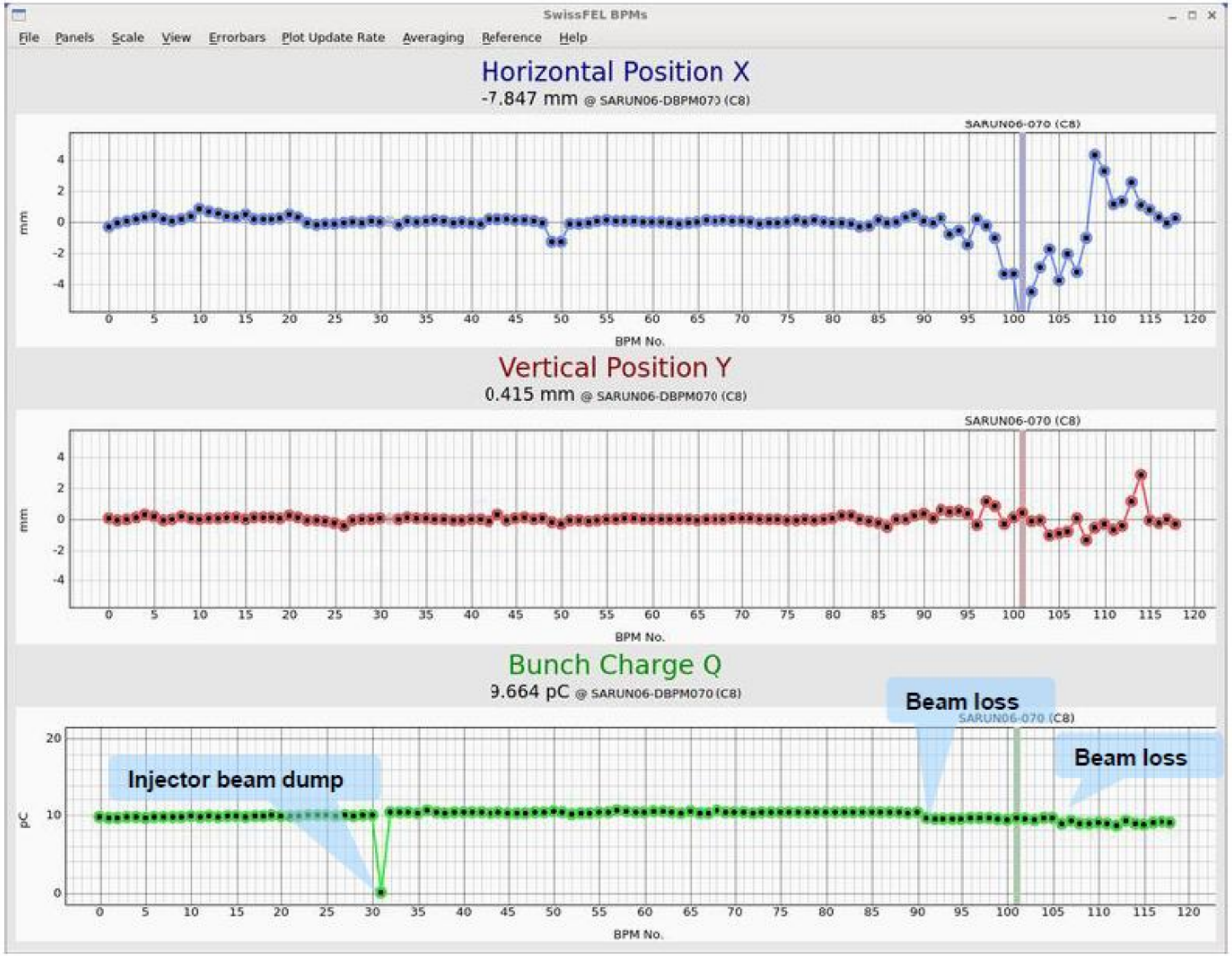




Present BPM usage in SwissFEL

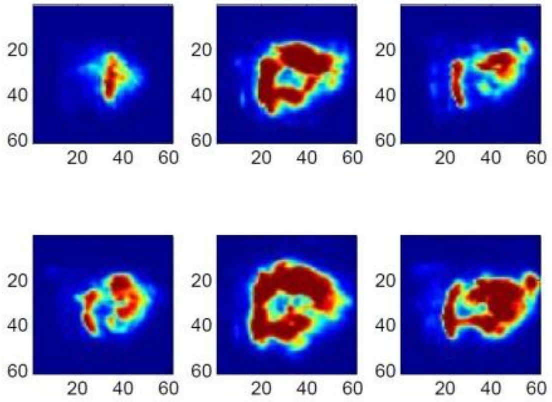
- 119 cavity-type BPMs in operation
- alignment of beam trajectory (minimize wakes in RF structures, e-beam / x-ray overlap)
- energy measurement in BC arms & dump spectrometers
- charge and transmission / loss measurement and coarse arrival time monitoring
- correction of position & charge dependency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

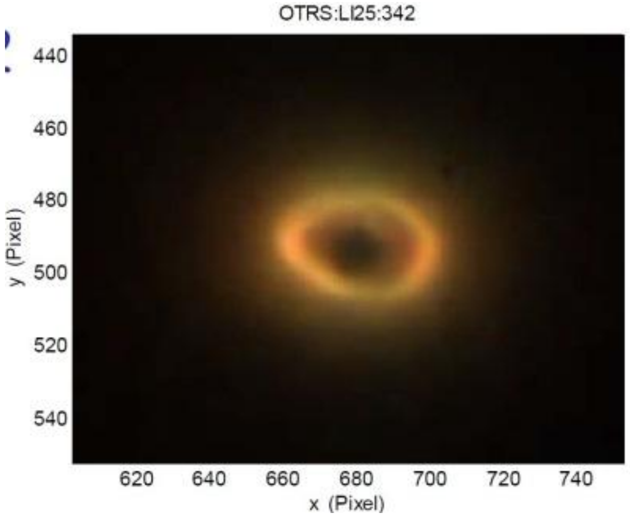
Commissioning Experience - BPM GUI



Transversal Beam Diagnostics Monitors

Optical Transition Radiators as 2-D Transverse Profile Monitors





The PROBLEM:

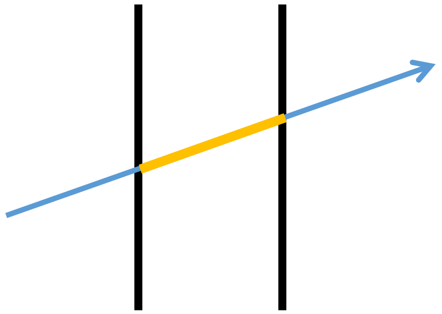
Coherent OTR has been observed for highly brilliant electron beams

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

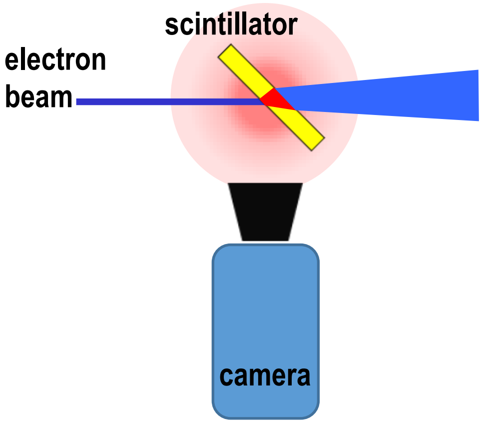
Another option – to use scintillator screens (also affected by the COTR) and try to suppress the generated COTR.

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

Schematic Setup and Main Properties of Scintillators as Screen Monitors



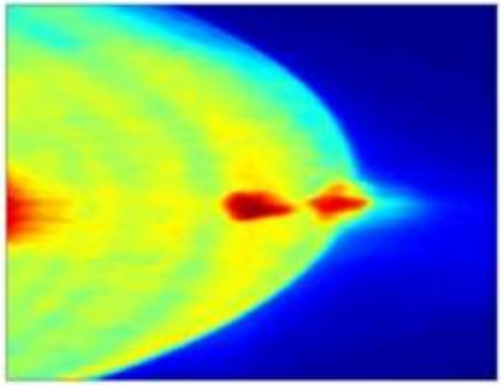
- electrons passing the scintillator crystal excite atoms and molecules, which then scintillate: re-emit the energy in the form of light
- visible light from scintillator crystals is radiated in 4π
- photons are created along the beam pass through scintillator crystal - a “light column” is formed

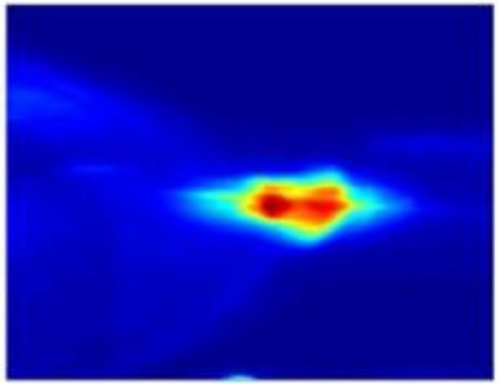


- scintillator crystals are very sensitive and radiation resistant
- multiple scattering in scintillator crystal increases beam divergence

- thickness of scintillator crystals and observation angles affect resolution

- **The problem: COTR is formed at the border scintillator/vacuum**

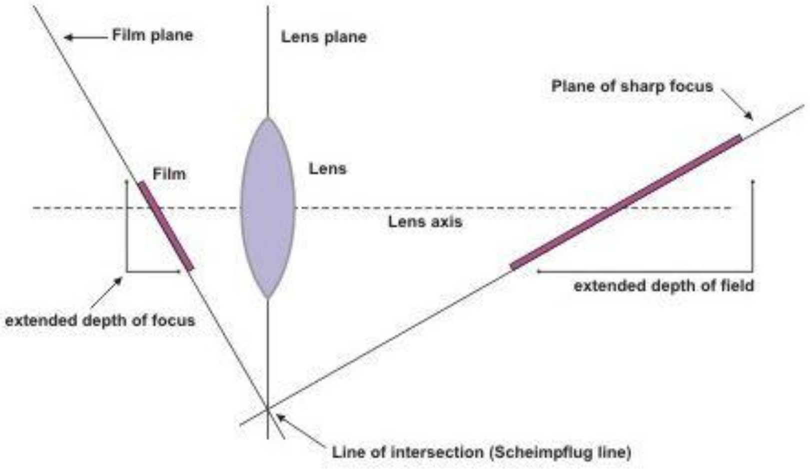




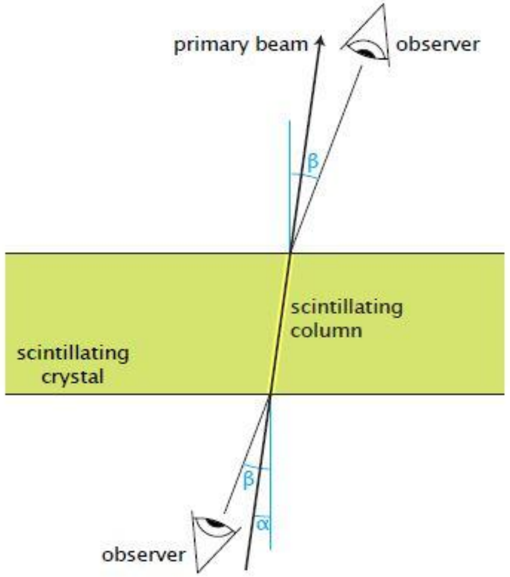
- COTR and CSR on OTR screen
- COTR and CSR on scintillator (LuAG screen)

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

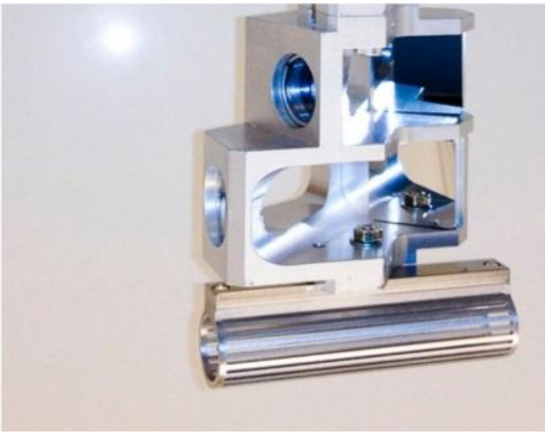


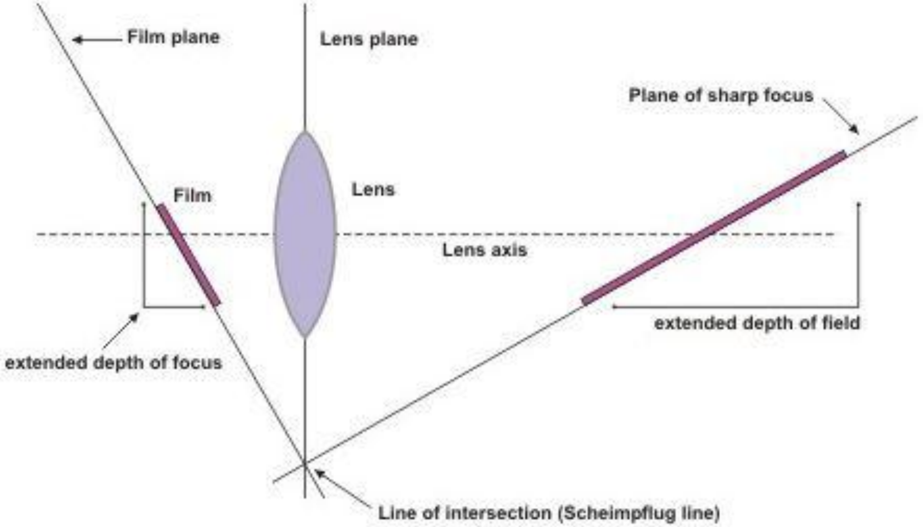
- use YAG or LuAG scintillator crystals instead of OTR
- observation of beam profile according to Snell's law of refraction
- one can image beams, which are smaller than scintillator thickness

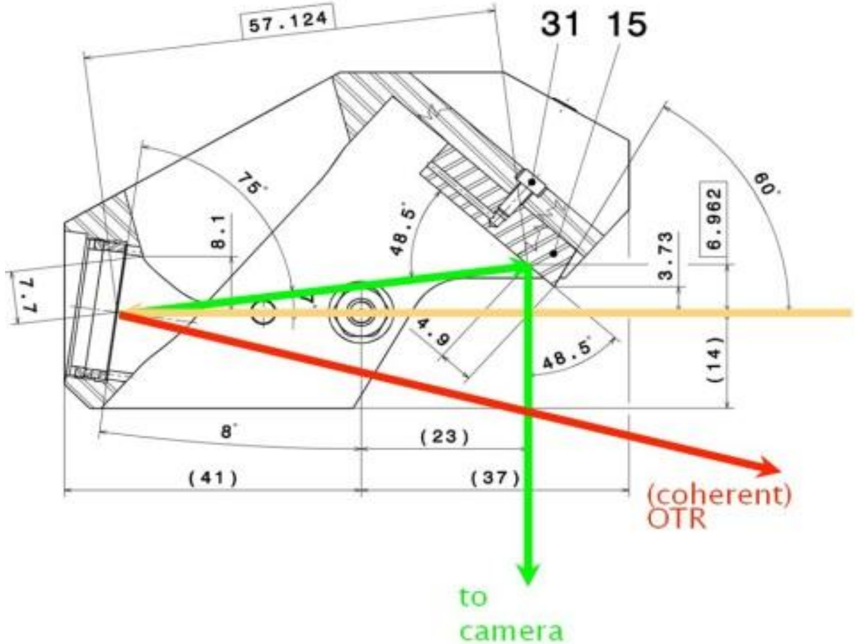


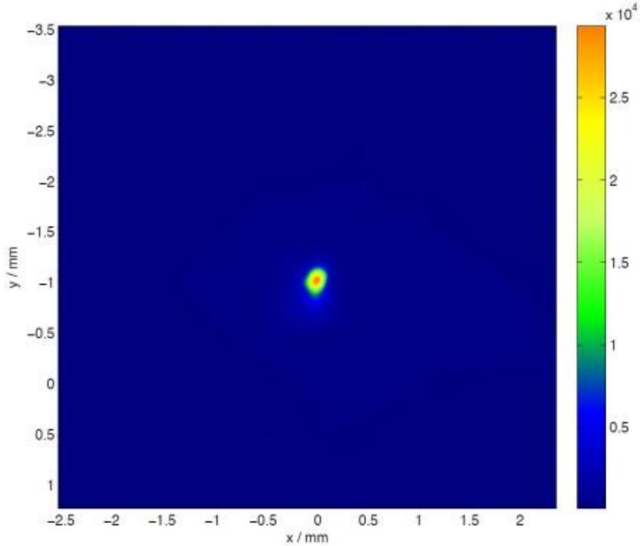
$$\frac{sin\beta}{sin\alpha} = n_{scint}$$

COTR suppression: spatial separation – SwissFEL profile monitors





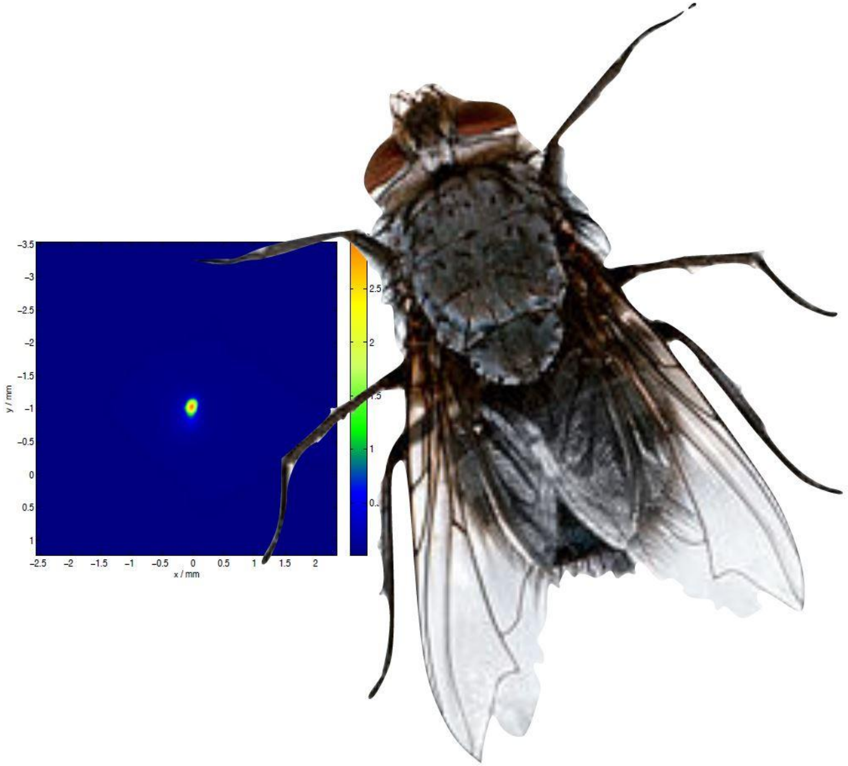




COTR suppression: spatial separation – SwissFEL profile monitors

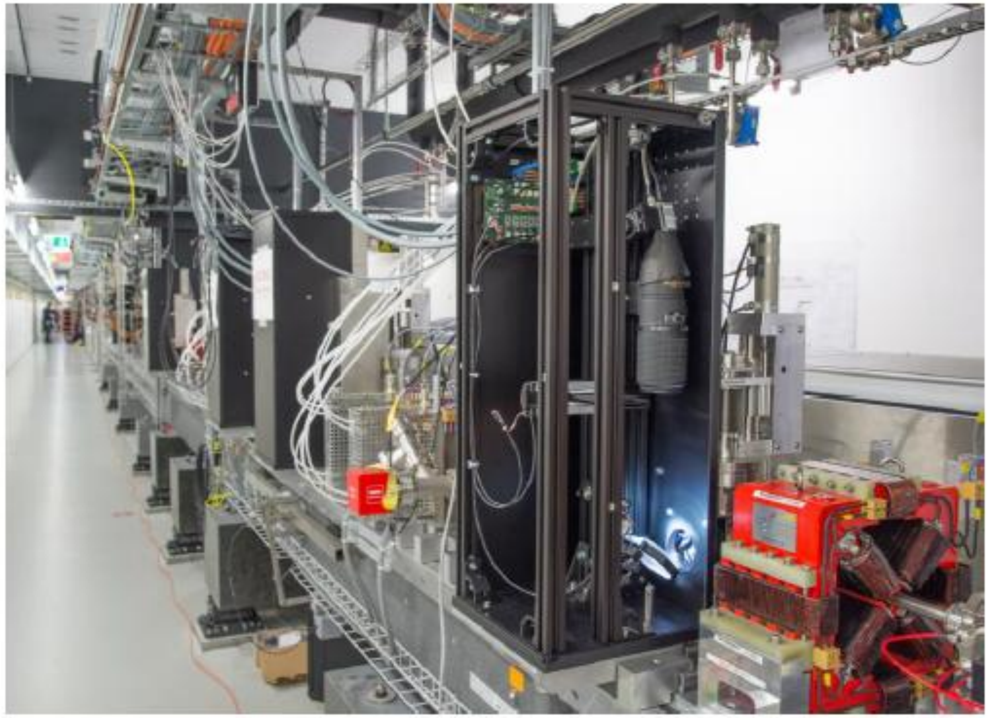
...and a comparison

to the «real world»



Commissioning Experience - Screen Monitors

View of Screen SwissFEL Monitor Stations



Screen Monitor Design Criteria

→ design of optical path avoids COTR blurring

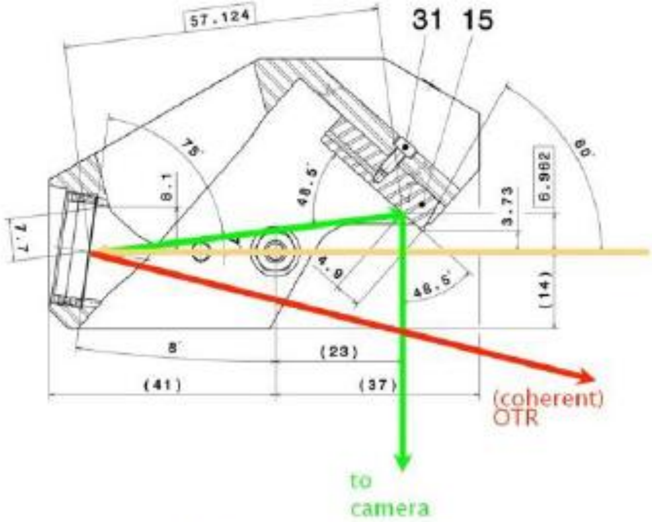
→ scintillators: LuAG and YAG crystals

→ 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

Screen Monitor Optical Path

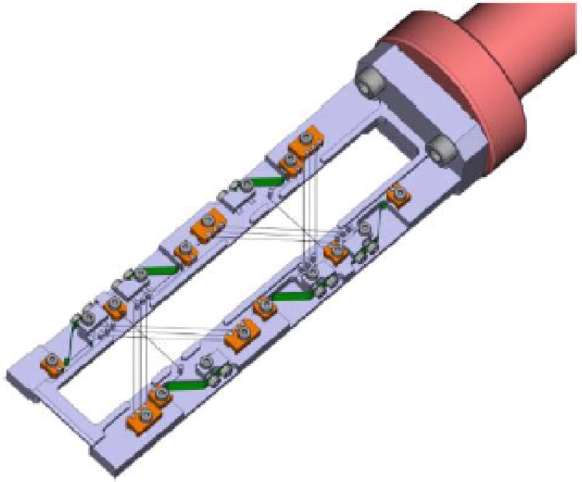


European Patent EP 2 700 979 A1

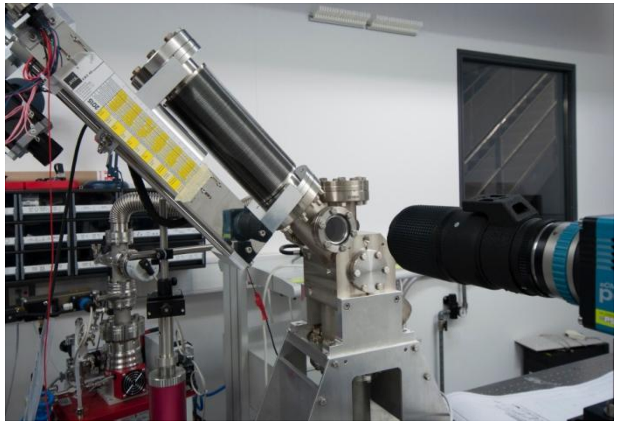
Wire Scanners

Commissioning Experience - Wire Scanners

SwissFEL Wire Scanner Fork

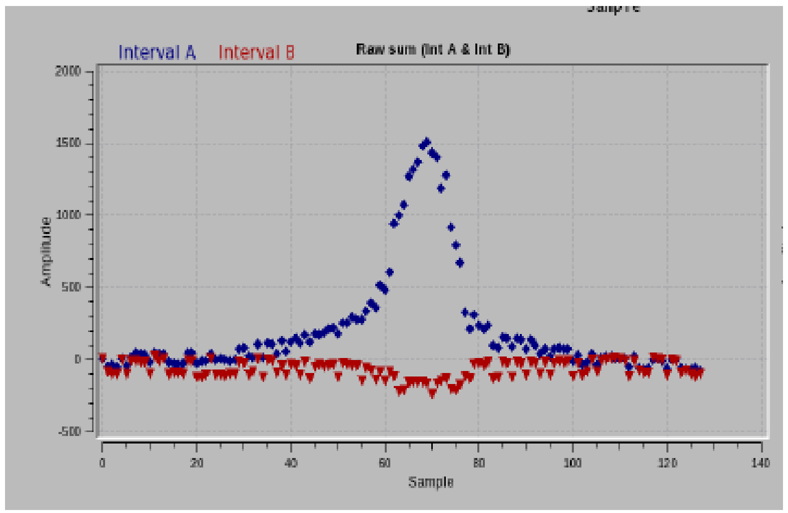


- WSC-fork equipped with 5 µm Tungsten and 12.5 µm Al(99):Si(1) wires (3 possible pin-slots for positioning X and Y wires)
- Beam loss ratio between Tungsten and Al(99):Si(1) wires: ~ 10 / 1
- wire vibration determined within stability limit of ≤ 1.3 µm rms (at Delta-Tau 2 –phase stepper motor speed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

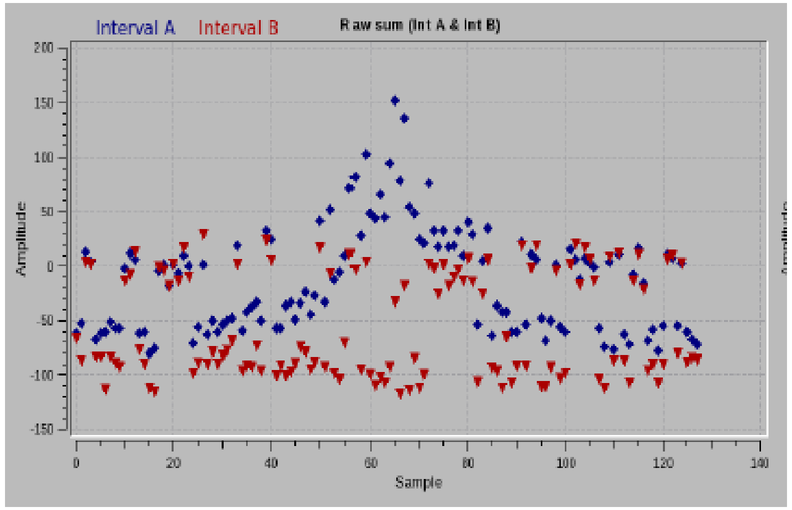


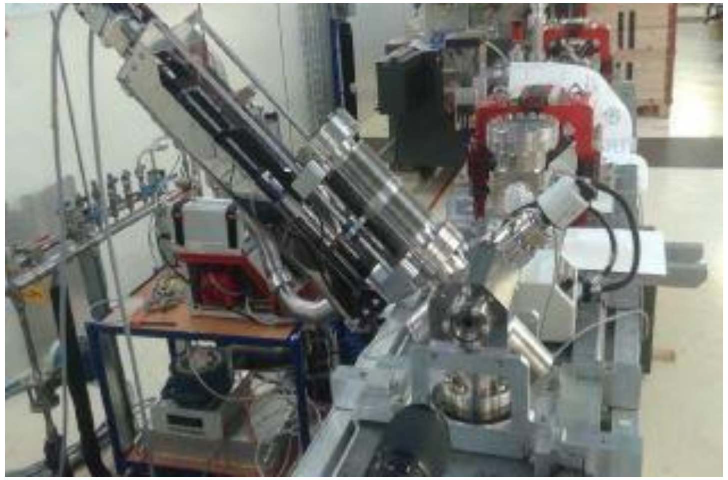
Examples of SwissFEL beam profile measurement taken at 148 MeV, 10 pC and 10 Hz…:

5 µm tungsten wire



12.5 µm Al(99):Si(1) wire



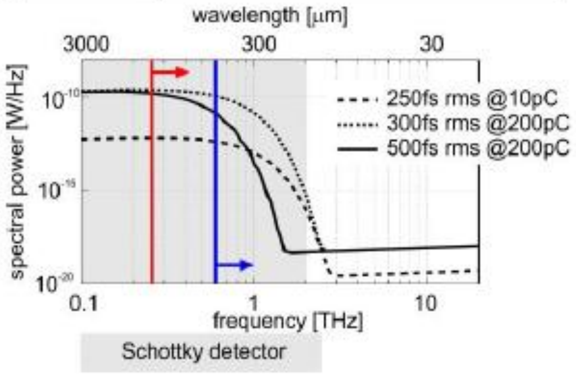


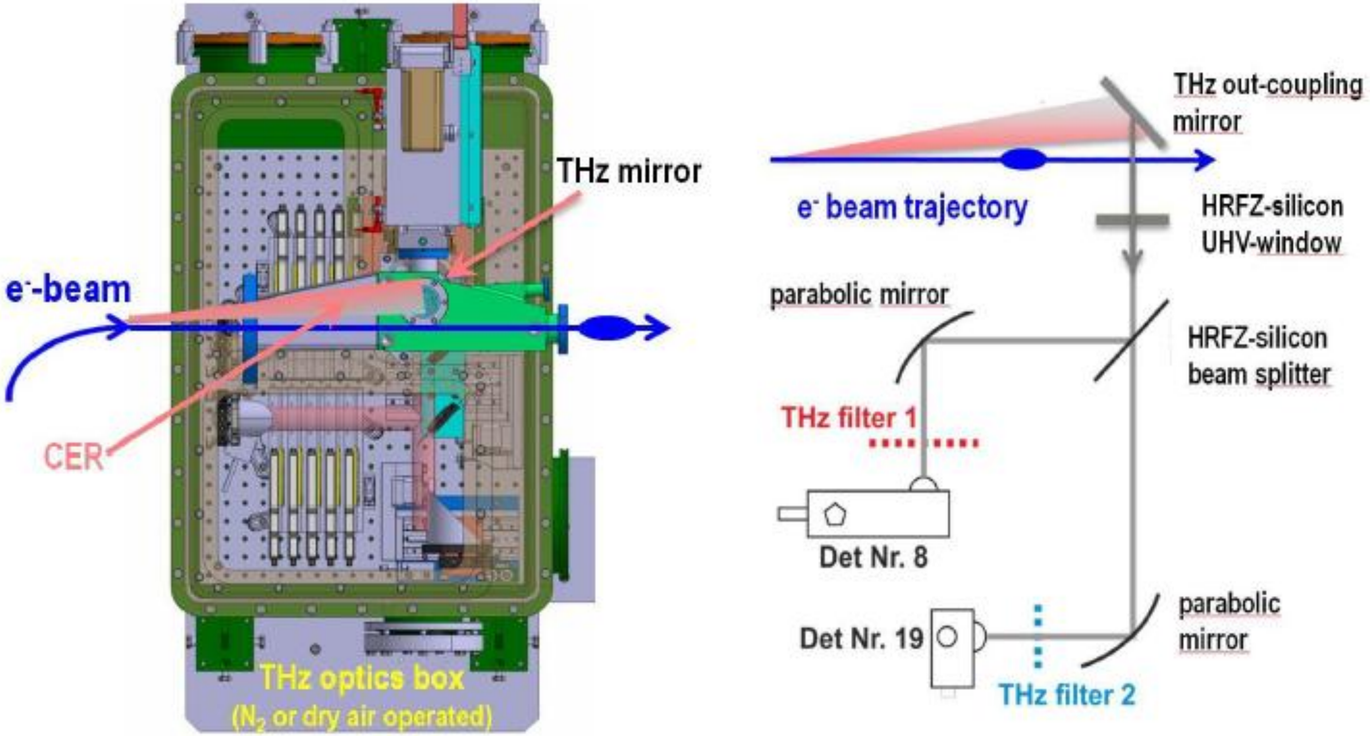
Bunch Compression Monitors

BC-1 Compression Monitor

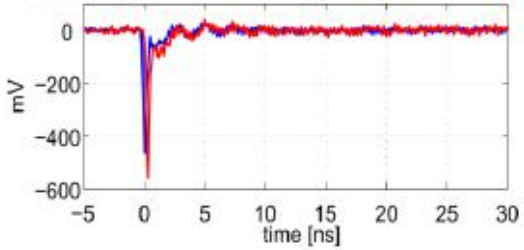
- use of coherent edge radiation from 4th BC-1 diplole (non-invasive)
- two signal paths for observation of different spectral (THz-) ranges for sensitivity to different bunch lengths
- use of THz high pass filters and broadband Schottky diodes
- ND-filters for intensity adjustment (bunch charge range: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

spectral range of CER and THz filters for BC-1





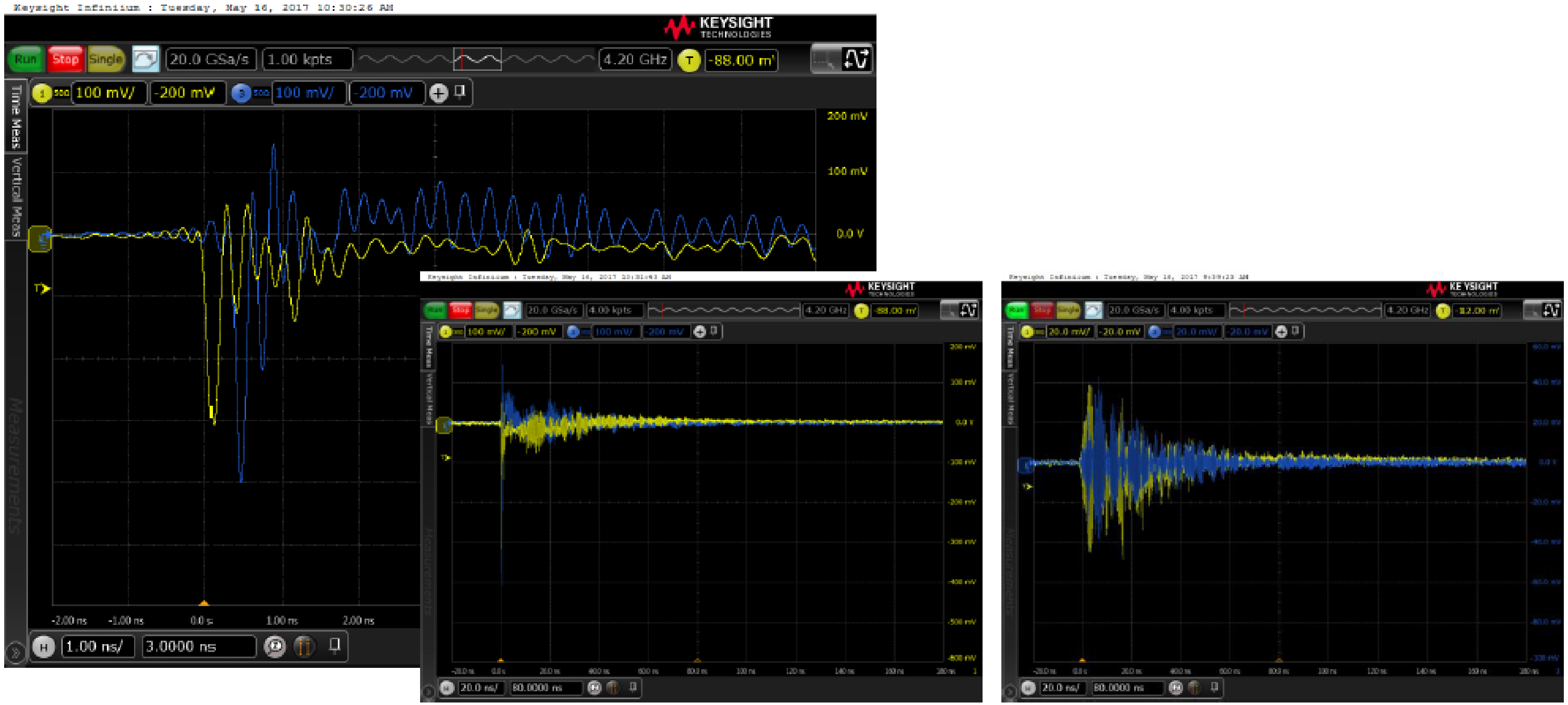
Schottky diodes raw signals (Det. 8 / 19)



First Signals from BC-1 Compression Monitor

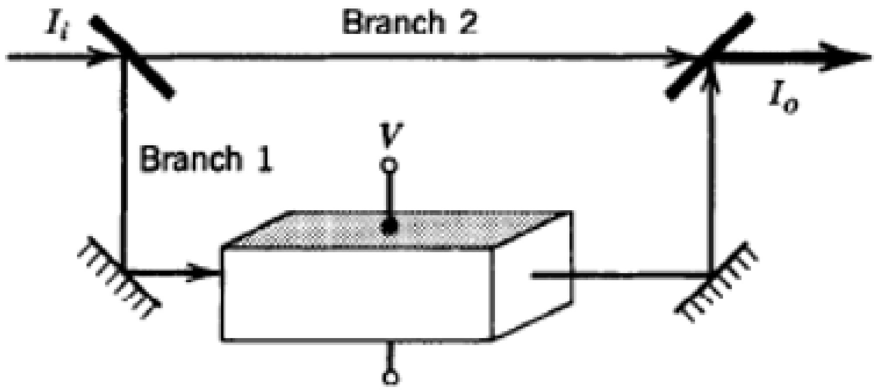
BC-1 Compression Monitor - Shottky Diodes with Spectral Filtering (THz-Range)

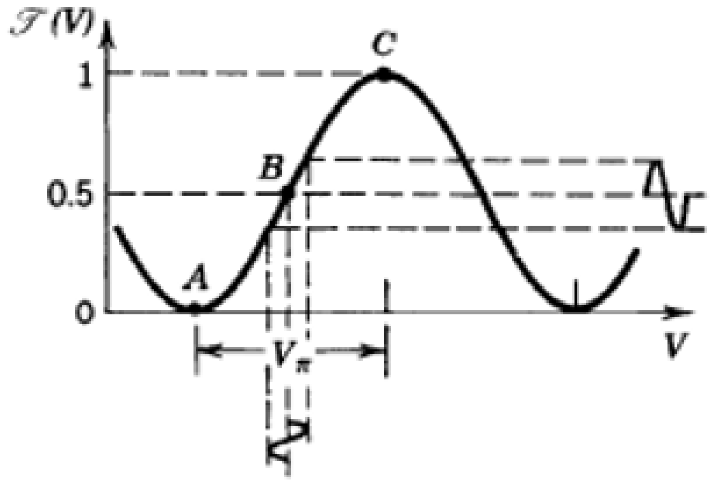
- first signals from BC-1 compression monitor have been seen on both Shottky diodes (with THz filters)
- sufficient CSR-signal for beam of E = 330 MeV, Q = 120 pC and τ = 460 fs (rms)
- Shottky diode signals are still “contaminated” with long ringing (wakefields or reflections?)
- dependency of signal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

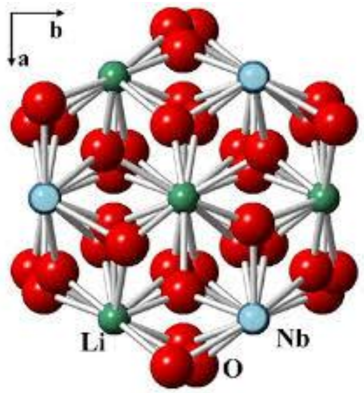


Bunch Arrival time Monitor (BAM)

Electro Optical Modulator (EOM) - Mach-Zehnder Interferometer

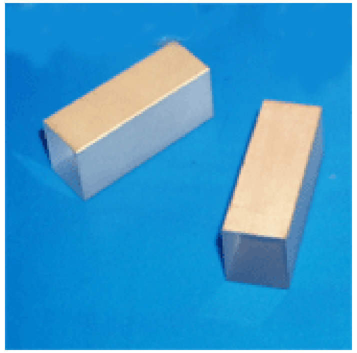




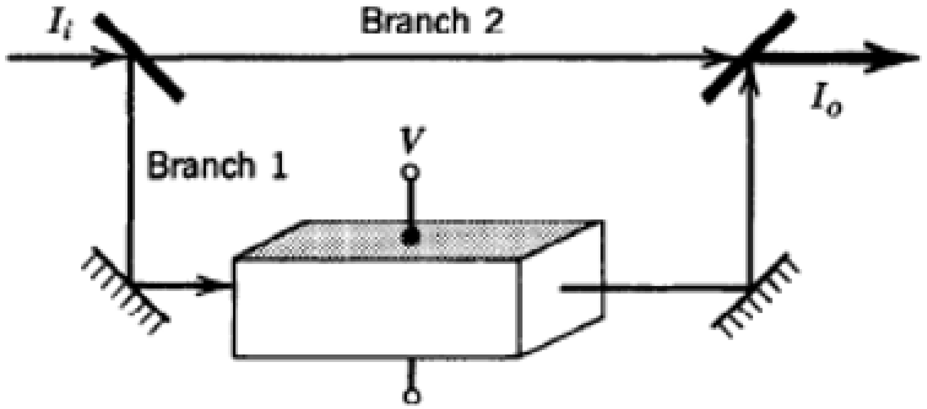


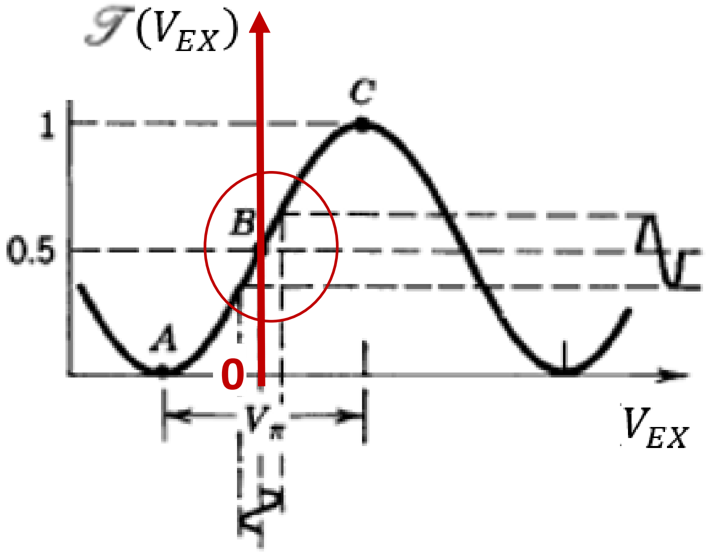
A phase modulator placed in one branch of a Mach–Zehnder interferometer can serve as an intensity modulator. The transmittance of the interferometer $\mathscr{T}(V) = I_o/I_i$ varies periodically with the applied voltage V. By operating in a limited region near point B, the device acts as a linear intensity modulator.

$$\mathscr{T}(V) = \cos^2\left(\frac{\varphi_0}{2} - \frac{\pi}{2}\frac{V}{V_\pi}\right).$$



LiNbO3
Pockels Cells





A phase modulator placed in one branch of a Mach–Zehnder interferometer can serve as an intensity modulator. The transmittance of the interferometer $\mathcal{T}(V) = I_o/I_i$ varies periodically with the applied voltage V. By operating in a limited region near point B, the device acts as a linear intensity modulator.

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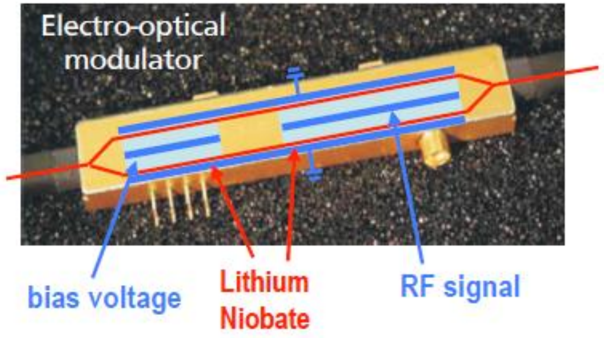
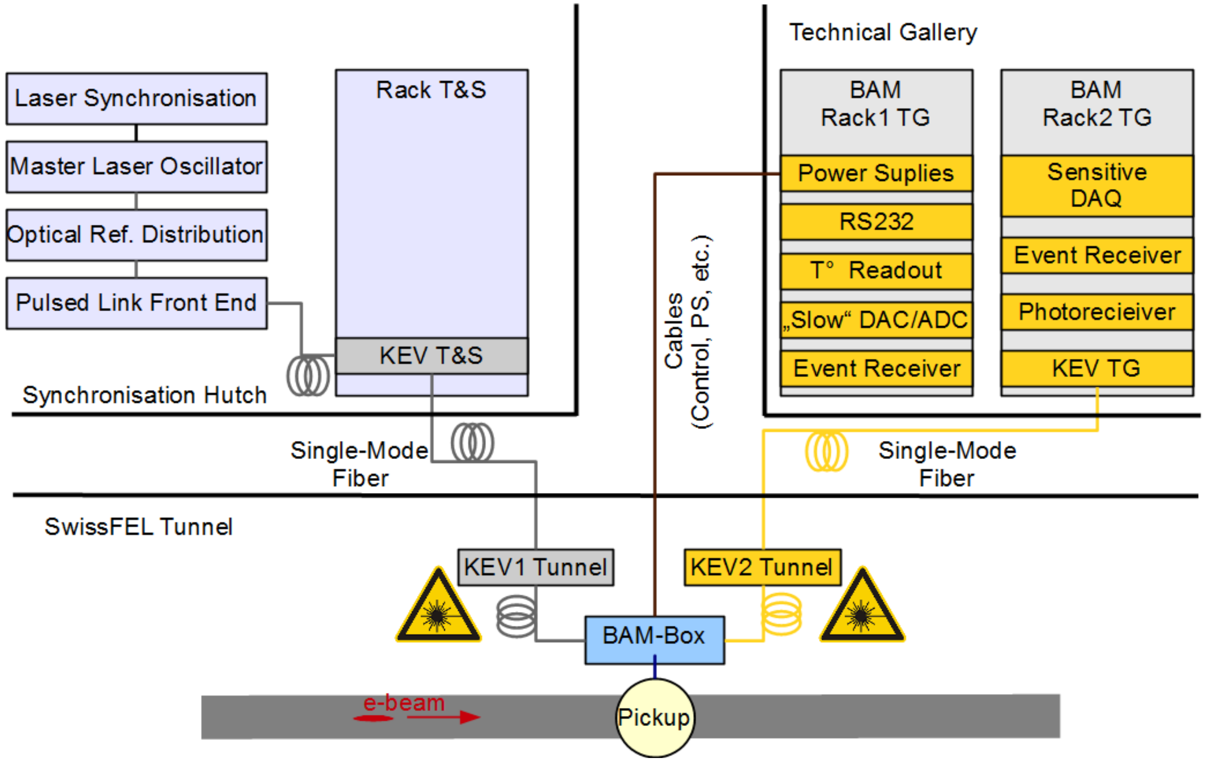


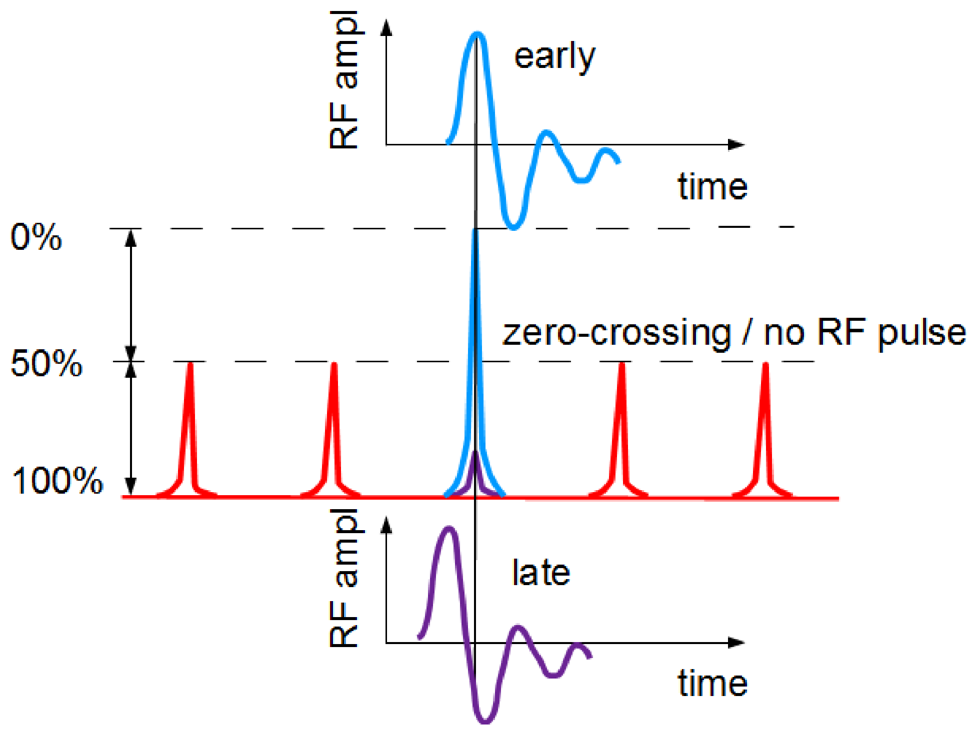
if $\varphi_0 = \pi$

$$V = \frac{V_\pi}{2} + V_{EX} = V_{bias} + V_{EX}$$

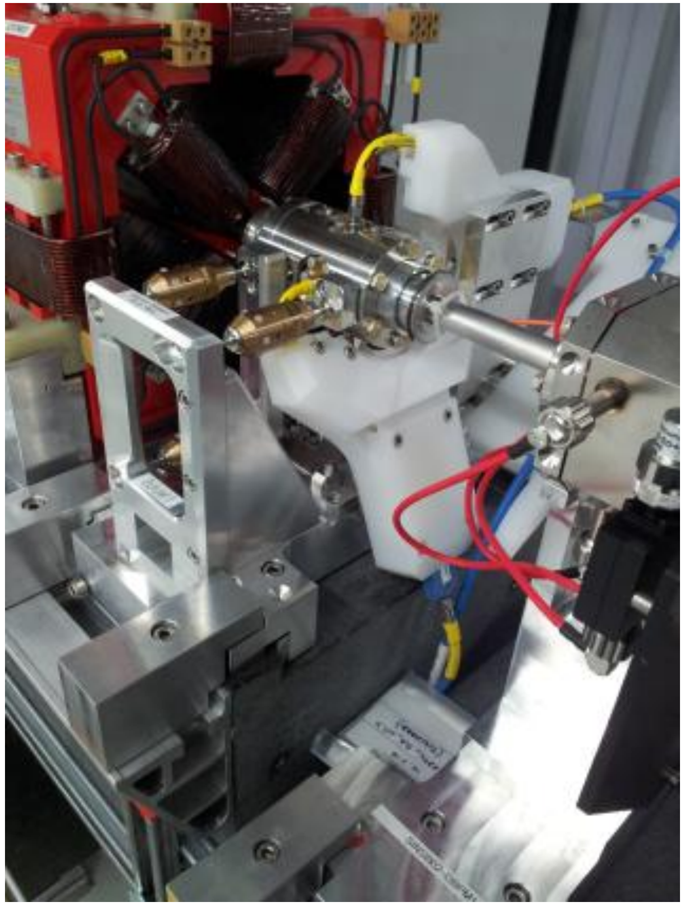
$$\mathcal{T}(V_{EX}) = \frac{1}{2} + \frac{1}{2}sin\left(\pi\frac{V_{EX}}{V_\pi}\right)$$

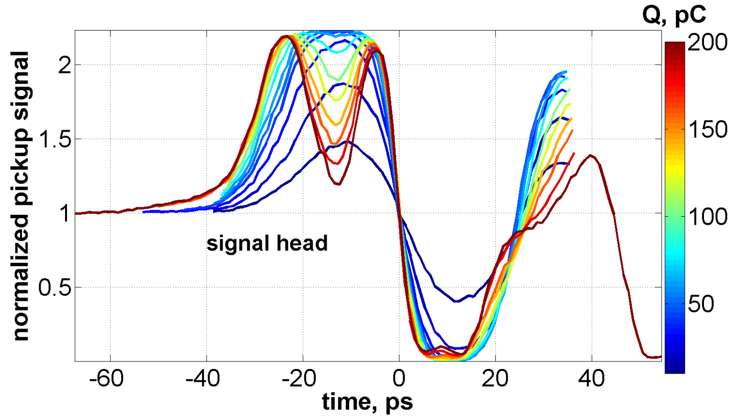
BAM basic ideas and layout

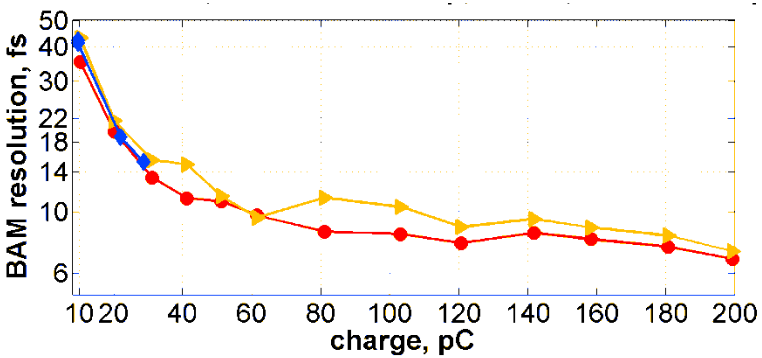


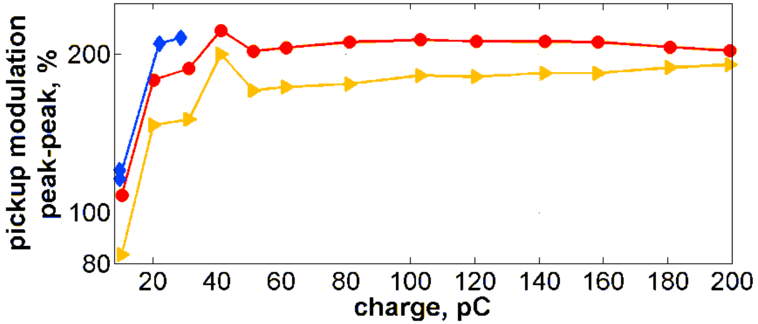


BAM pickup





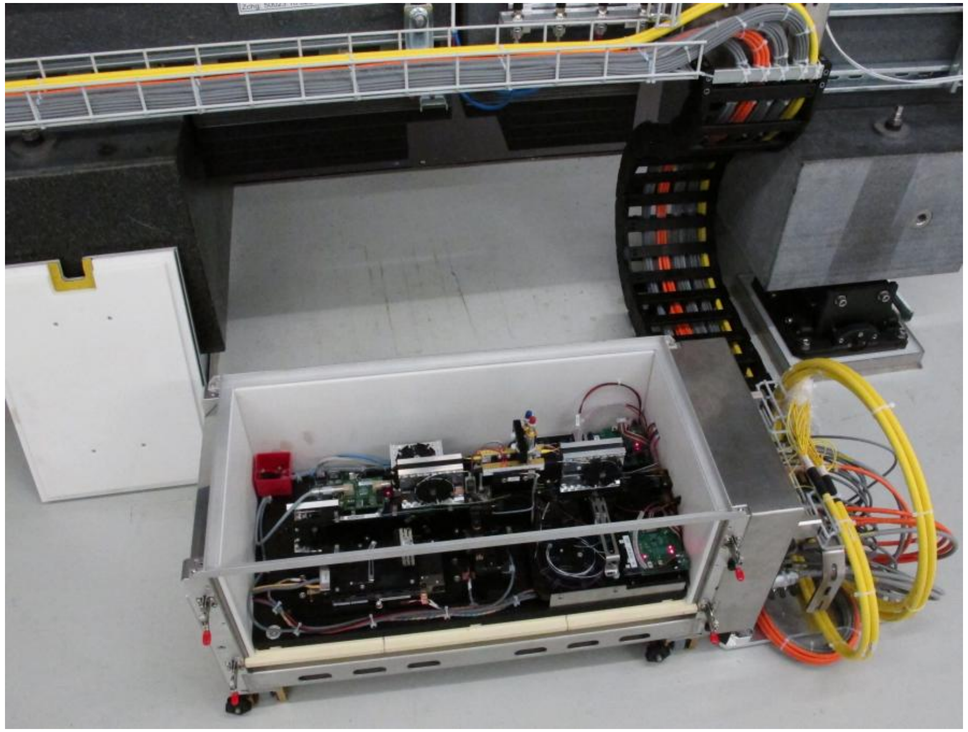


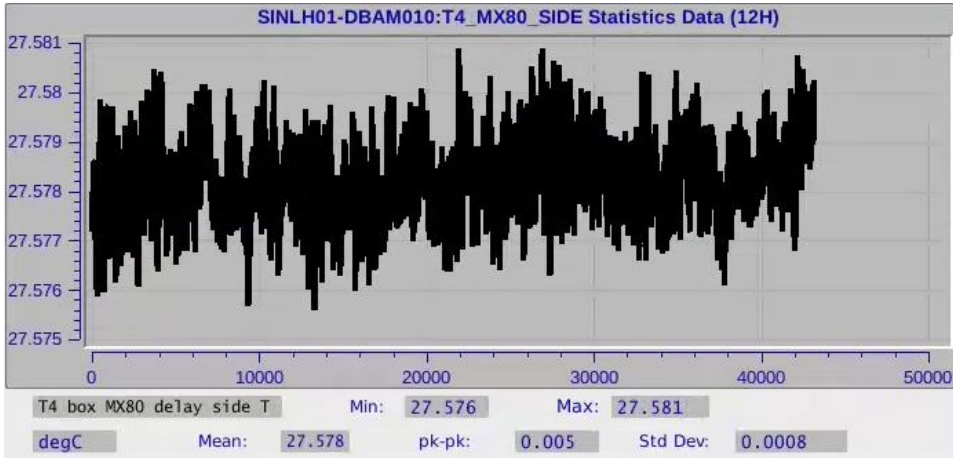


- Pickup chamber, 16 mm beam pipe diameter
- 40 GHz button pickups, feedthrough adapted to the PSI beam pipe diameter

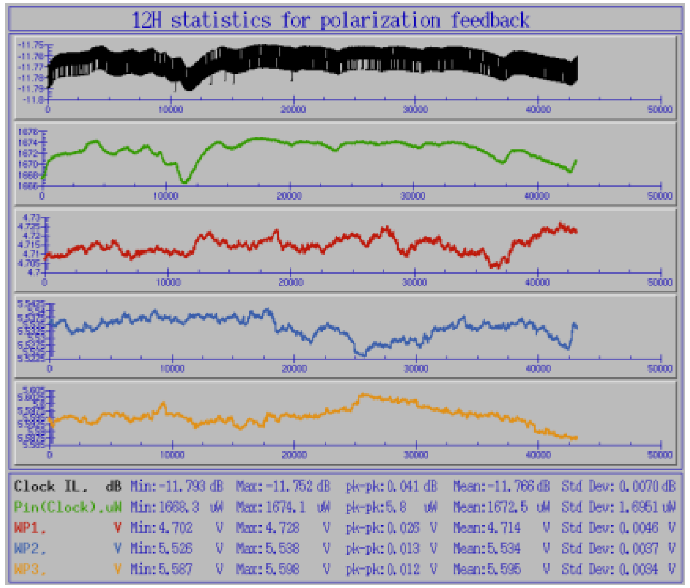
BAM Box

- TEC controlled
- Acoustical and thermal insulation
- Shielded against radiation
- EOM bias stabilization
- Accessible for servicing

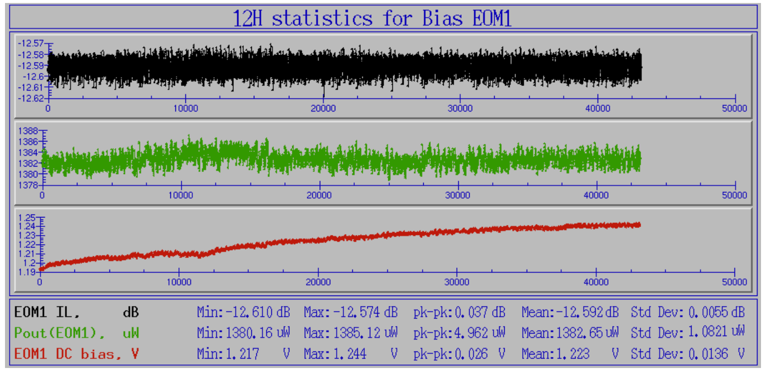




Typical T° Stability over 12h: 5 mK pk-pk



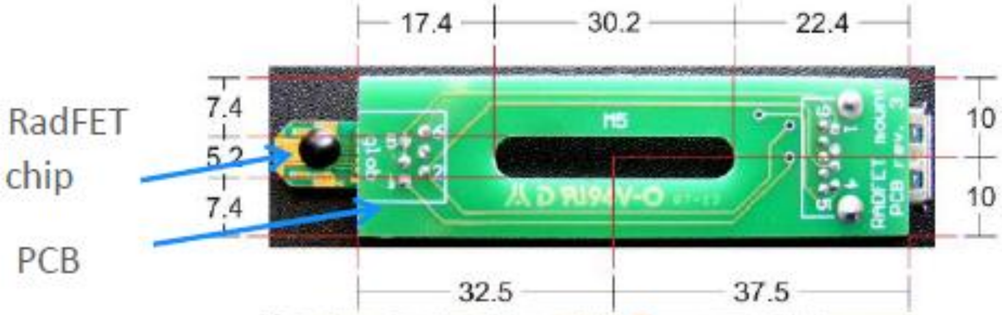
Polarization stabilization: 12 h statistics



EOM bias stabilization: 12 h statistics

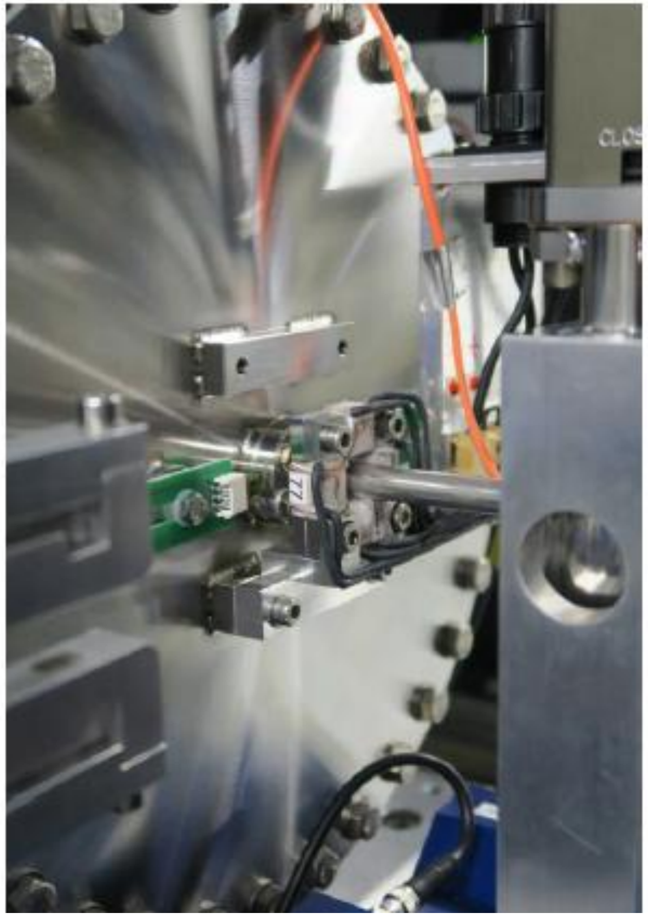
Radiation Dose Monitors

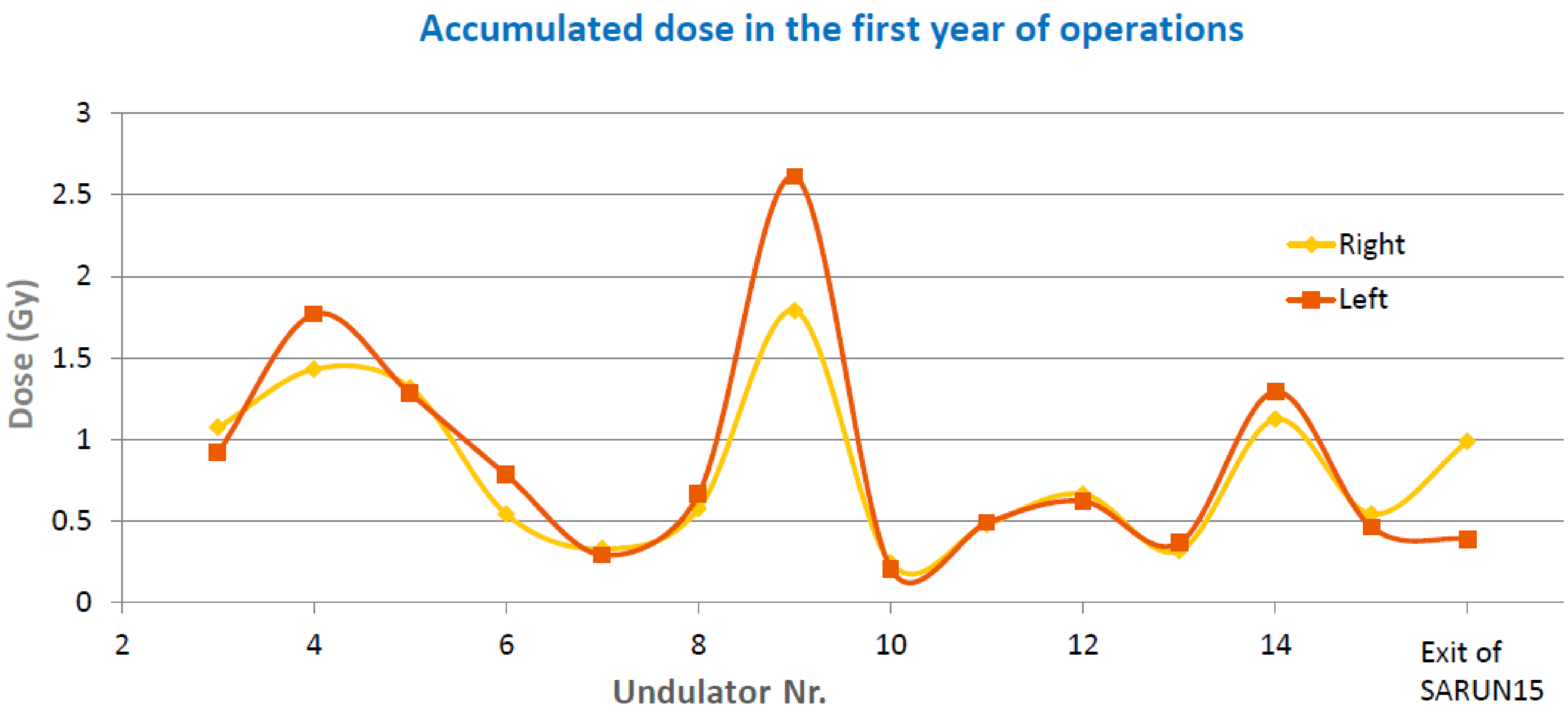
Dose monitoring



- To track accumulated dose
- Distance of RadFET to the beam pipe flange is ~1mm
- Minimum integration time 20 seconds
- Undulator protection:
  Closes MPS shutter if permitted dose rate (e.g., 0.05Gy/20s) or daily dose limit is exceeded

- ARAMIS: 42x RadFETs → 13 DOSFET controllers
- ATHOS: 18x RadFETs → 4 DOSFET controllers

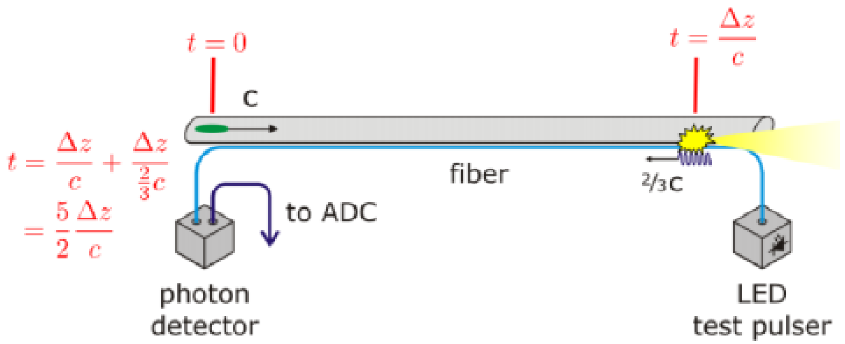


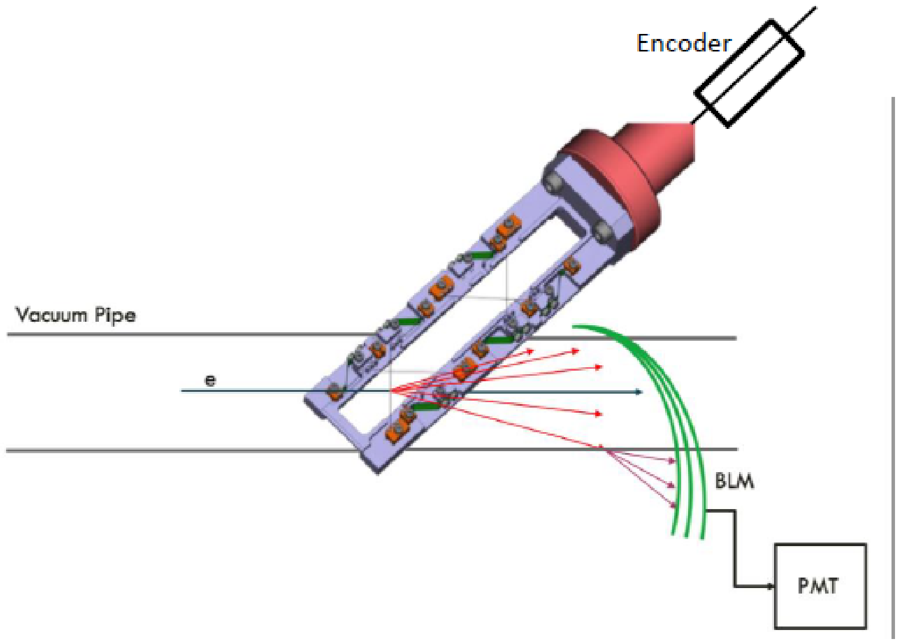


Accumulated dose in the first year of operations
Dose (Gy)
3
2.5
2
1.5
1
0.5
0
2
4
6
8
10
12
14
Exit of
SARUN15
Undulator Nr.
Right
Left

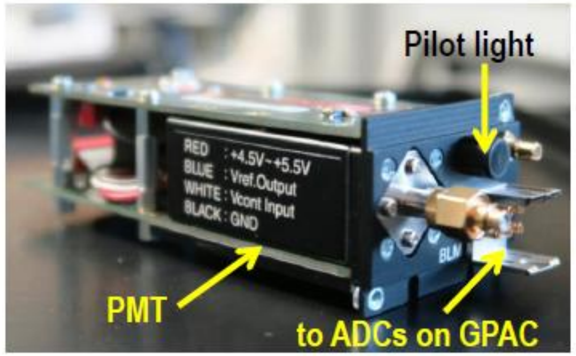
Beam loss monitors at SwissFEL

- Loss tracking due to:
  - Insertion of screens, collimators, slits
  - Beam alignment
  - Wire insertions
- Two types of loss monitors:
  - Scintillator based, for localized losses (BLM)
  - Optical fiber for tracking loss positions along the machine (LLM)



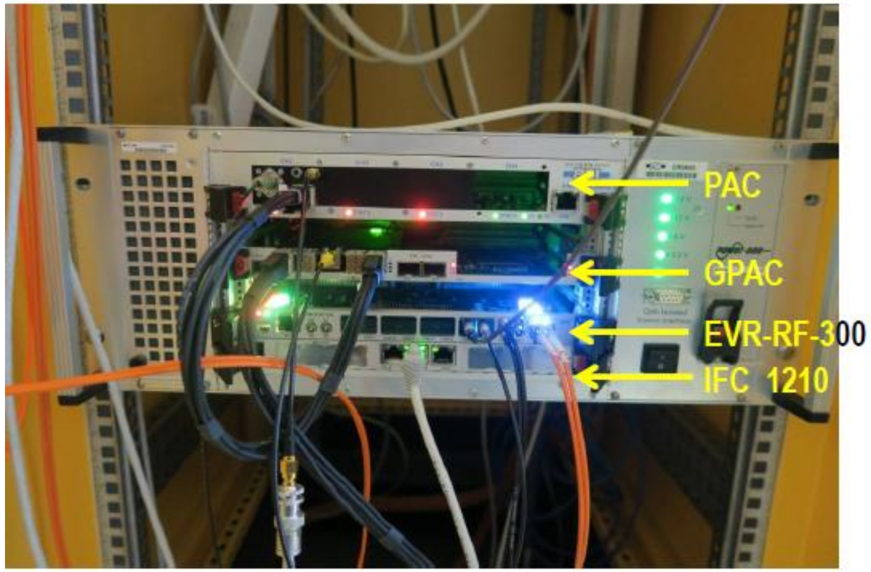


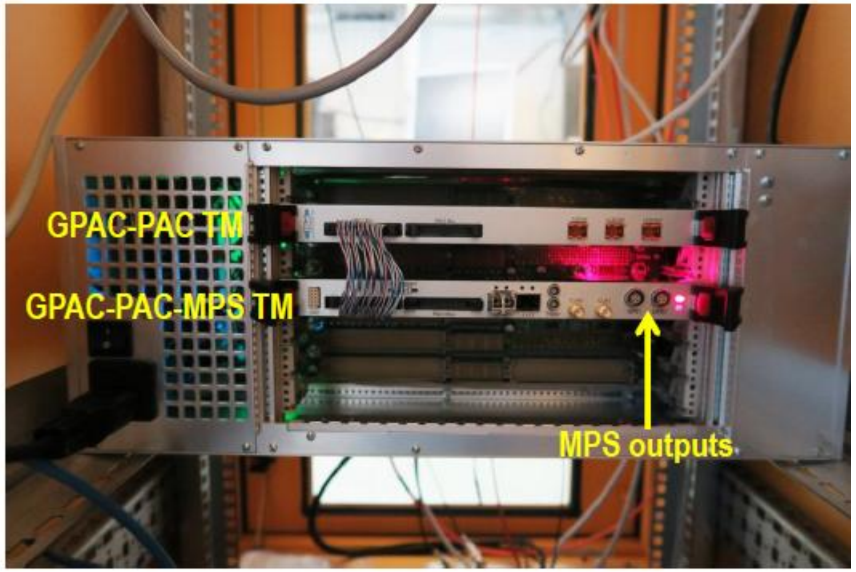
BLM DAQ system overview



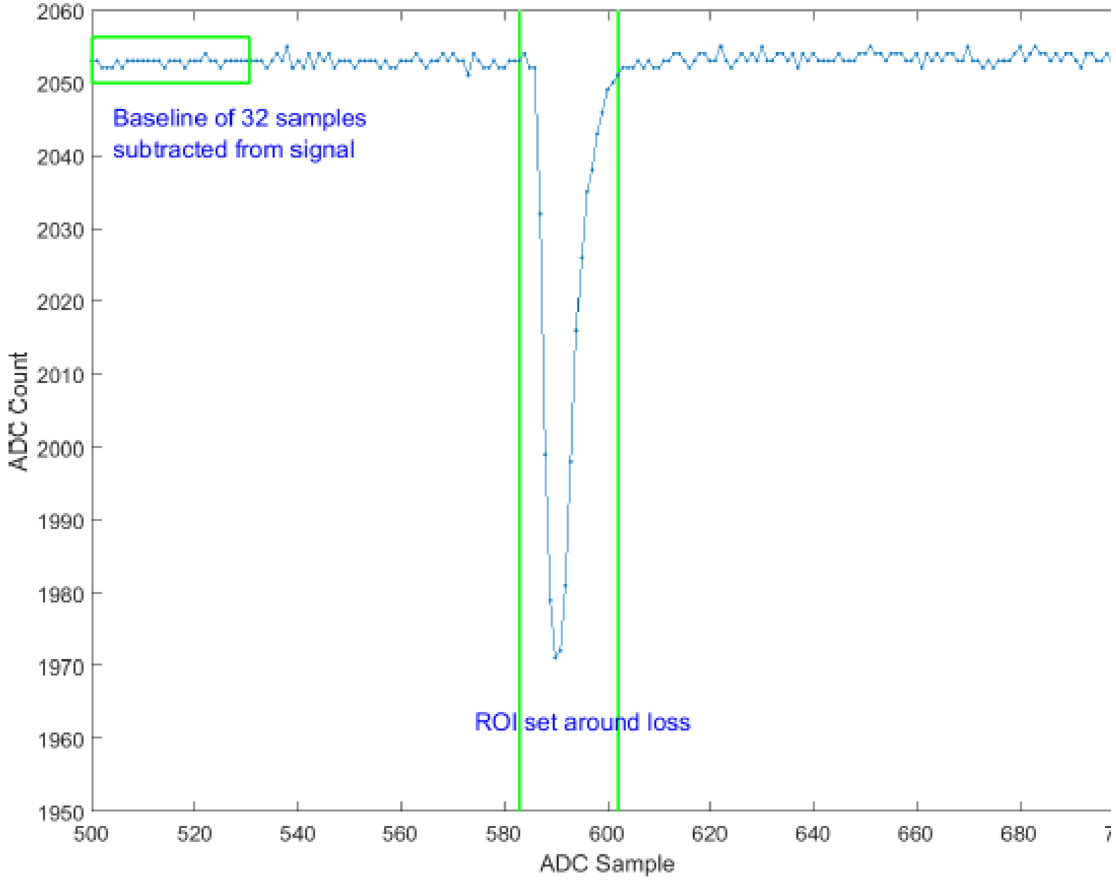
- Analog front-end & digital backend developed at PSI
- Cost reduction: using same readout chain for all
- Common firmware and software solutions

ARAMIS + ATHOS = 28 Systems

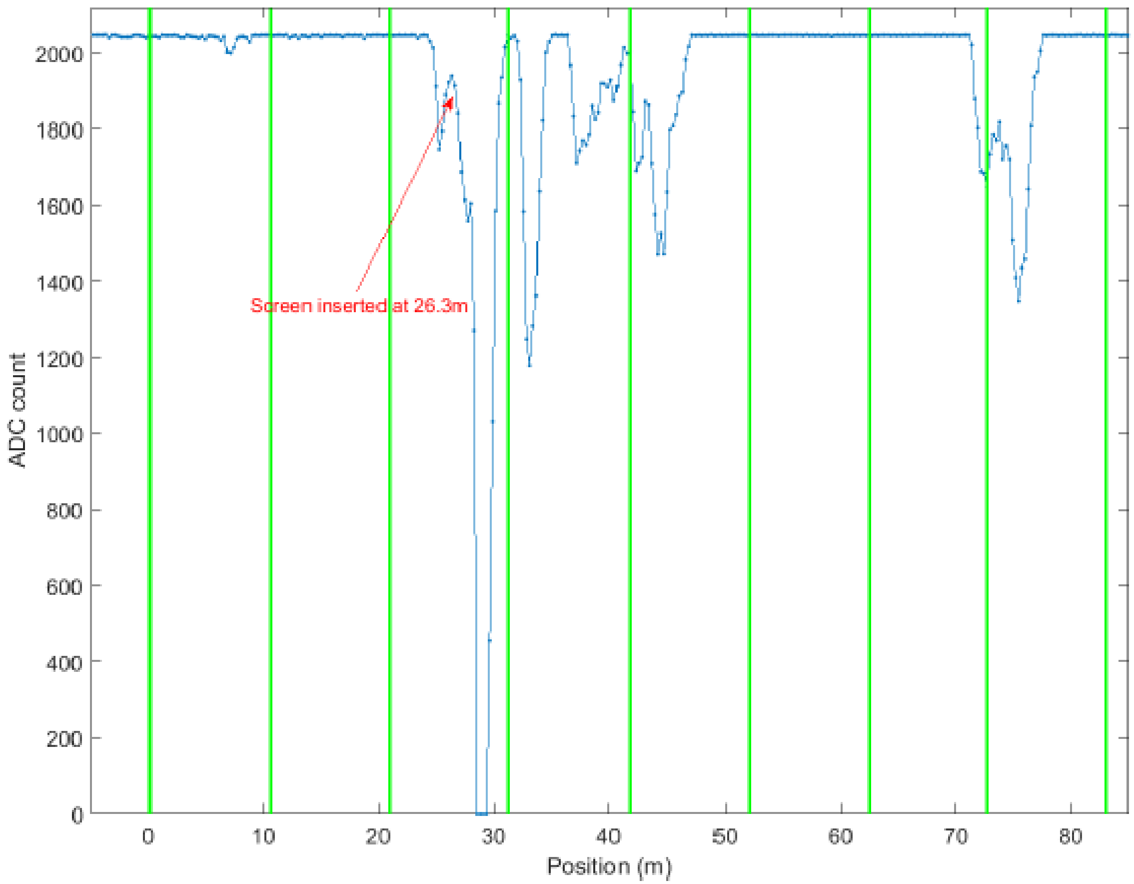




Beam loss monitor



Longitudinal loss monitor



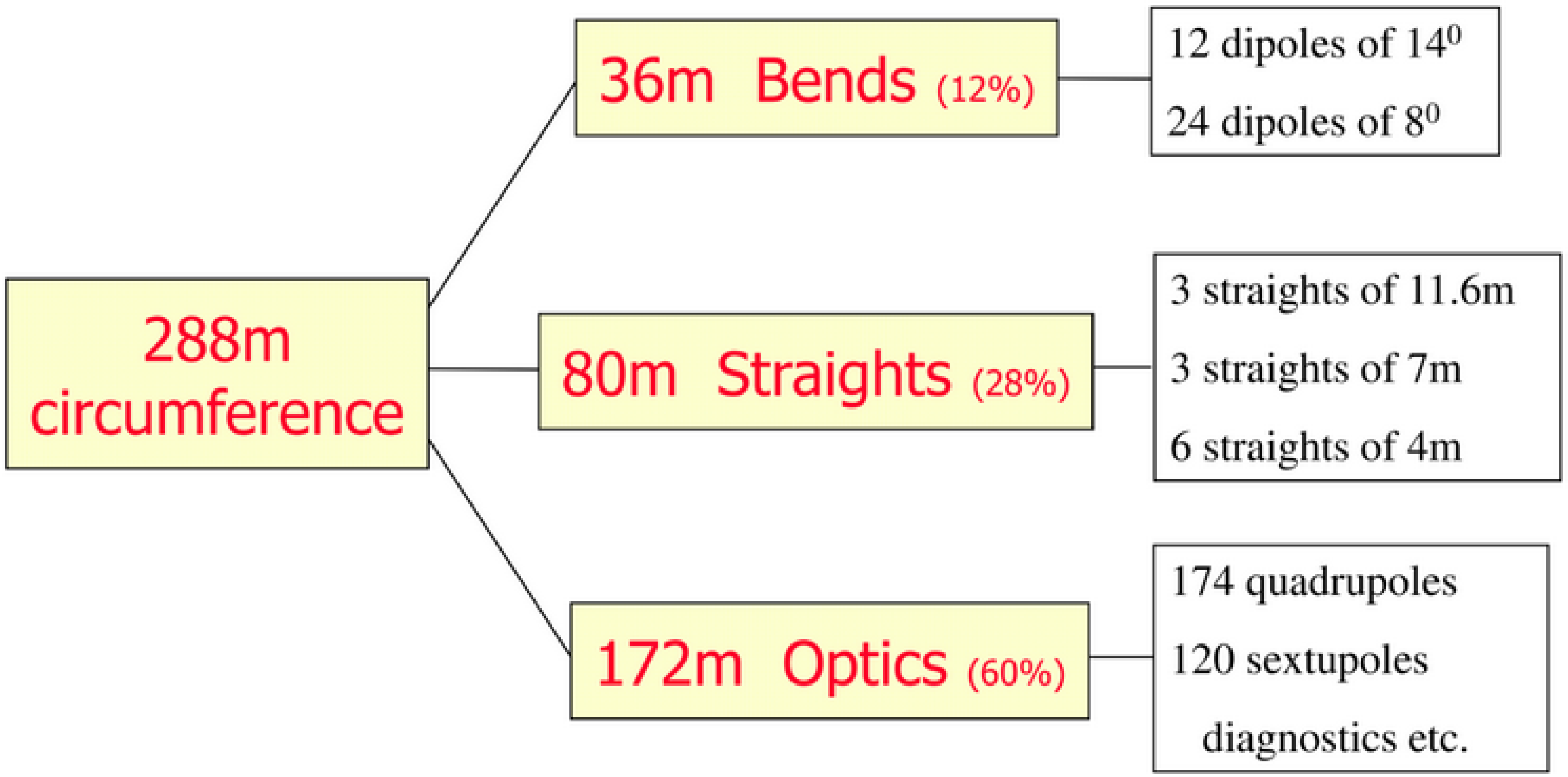
Overview of SwissFEL Diagnostics Components (Phase-1, ARAMIS)

→ 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) BPMs (0.1% relative)
→ Beam Loss Monitors:	38 scintillating monitors (high sensitivity) 8 distributed Cherenkov monitors
→ Dose Rate Monitors:	32 RadFET 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)

SLS
(140m Diameter)

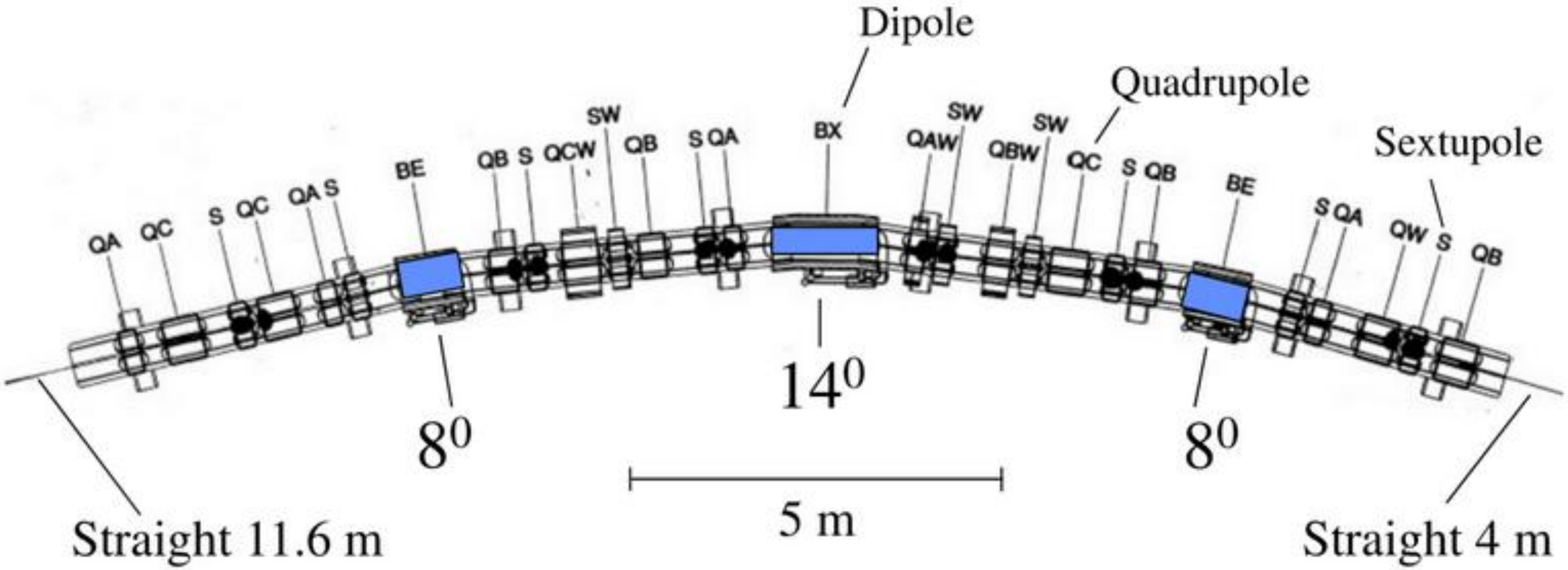
Swiss	Light	Source
Synchrotron	Lichtquelle	Schweiz
Source	Lumière	Suisse
Sorgente	Luce	Svizzera

Allocation of Space for Storage Ring



Inside SLS

SLS 30^0 Arc

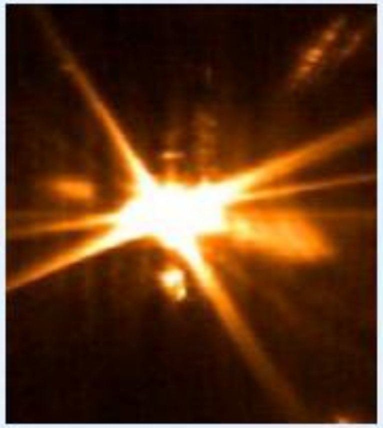


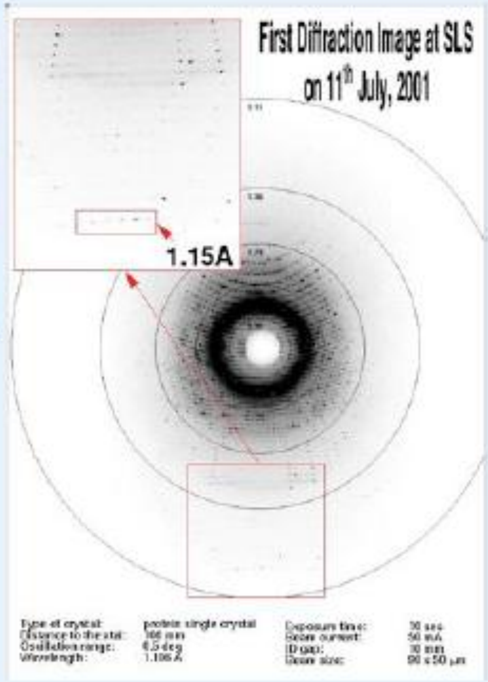
TBA-lattice

(Triple Bend Achromat)

Swiss Light Source - Short History and Some Key Parameters

	1990	First ideas for a **Swiss Light Source**
	1993	Conceptual **Design** Report
June	1997	**Approval** by Swiss Government
June	1999	Finalization of **Building**
Dec.	2000	First **Stored Beam**
June	2001	Design current **400 mA** reached **Top up** operation started
July	2001	First **experiments**
Jan.	2005	**Laser beam slicing**
May	2006	**3 Tesla super bends**





• **Beam Energy**	2.4 GeV	• **Energy Spread**	0.09 %
• **Circumference**	288 m	• **Beam Current**	400 mA (top-up operation)
• **Emittances**		• **Life Time**	~ 8 h
horizontal	5 … 6.8 nm rad	• **Stability**	< 1 μm (photon beam at front end)
vertical	3 … 10 pm rad		

Swiss Light Source - Top-Up Operation

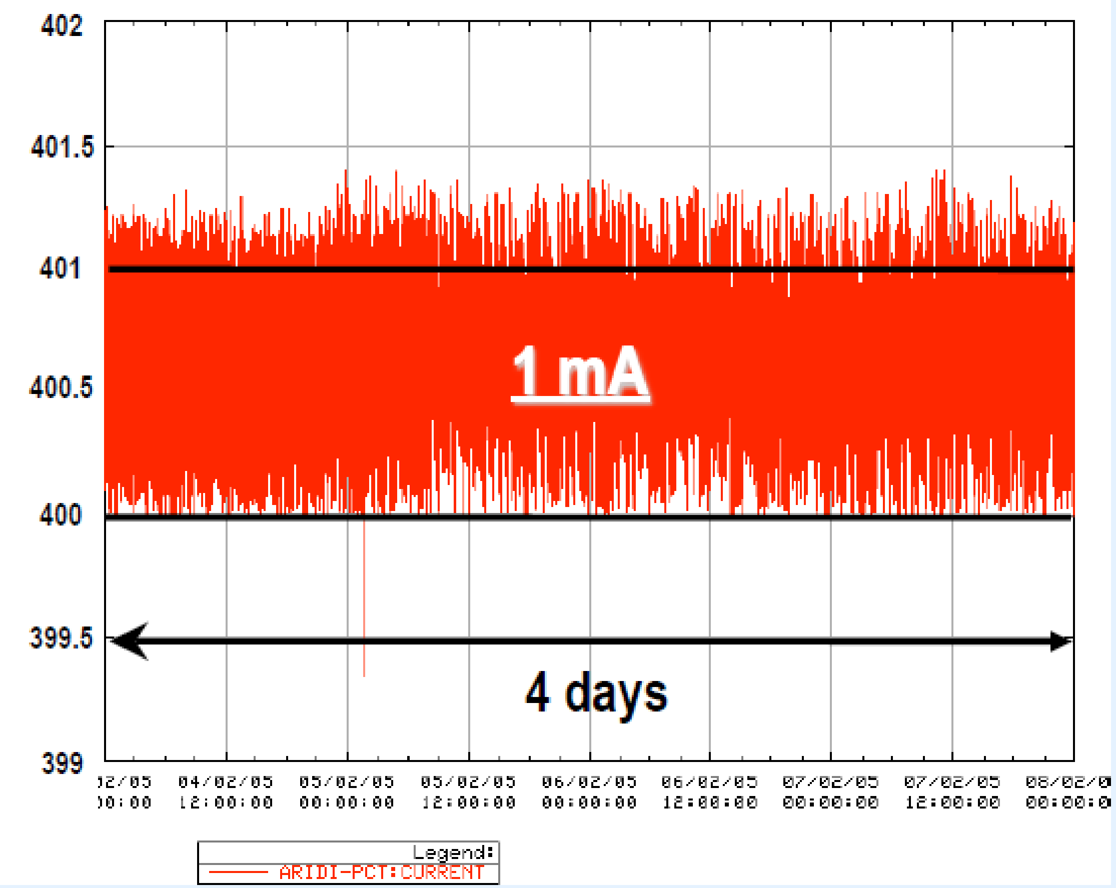
reason: low lifetime

refill: 1...2 minutes

current: 400 ±1 mA

- ☑ thermal stability
- ☑ constant BPM gain

top up is a prerequisite for sub-μm beam stability at the beam lines!



The key to efficient "top-up" operation is the SLS booster

- ☑ High injection efficiency (ε ~ 10 nm)
- ☑ Low operating costs (total power ~ 30 kW)
- ☑ High reliability (simplicity and relaxed optics) with large circumference and many FODO cells using combined function magnets

Some important SLS highlights

SLS Synchrotron Radiation Monitor

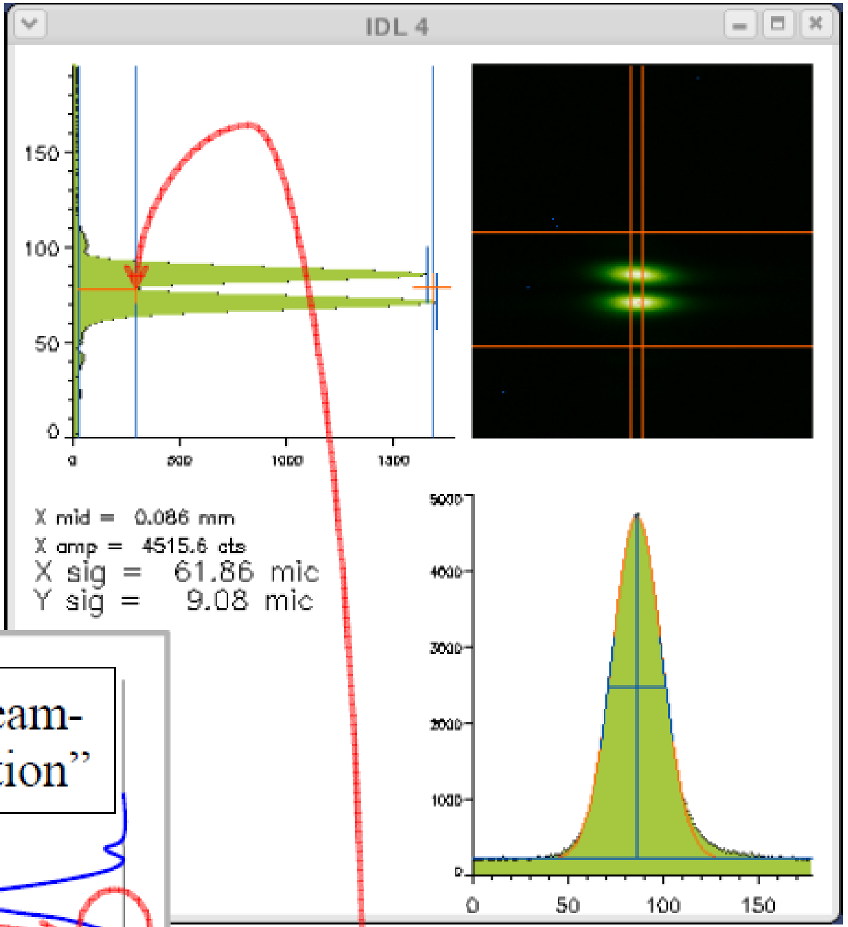
The π -polarization method[*)]:

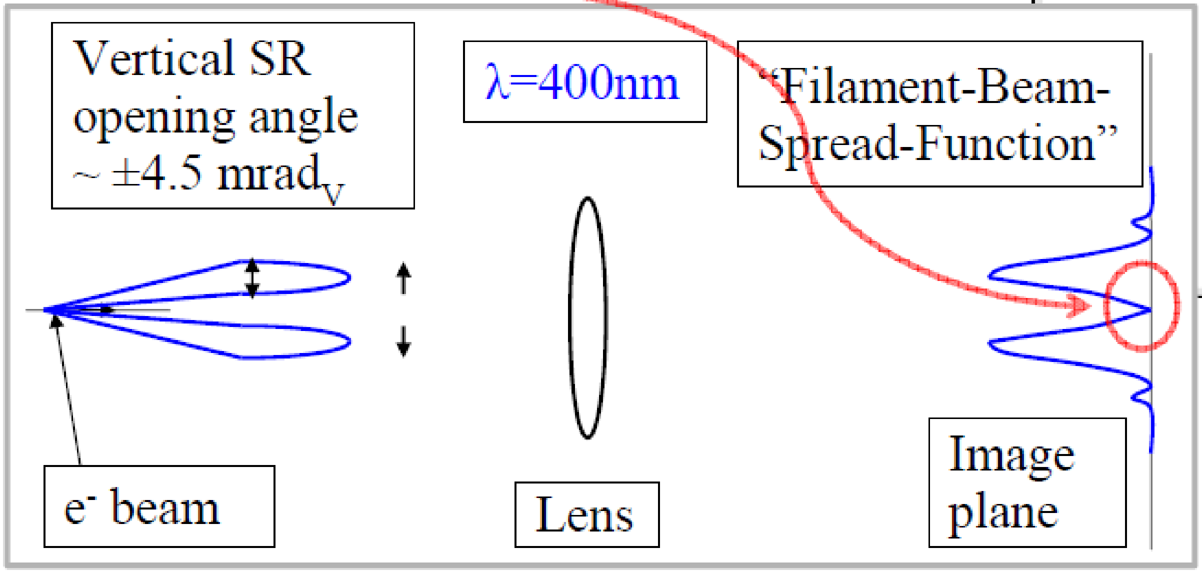
An image of the beam is formed from vertically polarized visible-UV synchrotron radiation.

A π phase shift between the two radiation lobes ==> $I_{y=0}=0$ in "FBSF"

(FBSF =filament beam spread function)

*) Chubar et. al.

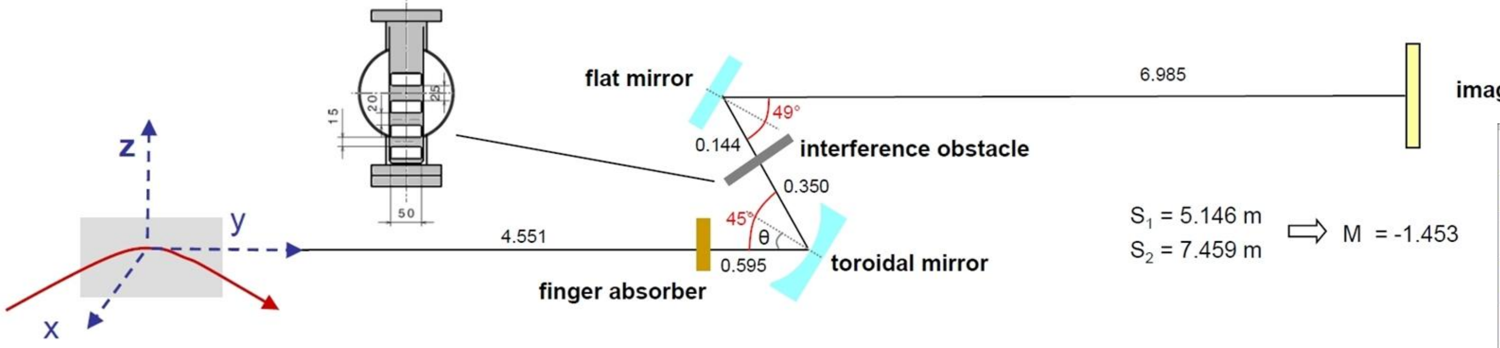


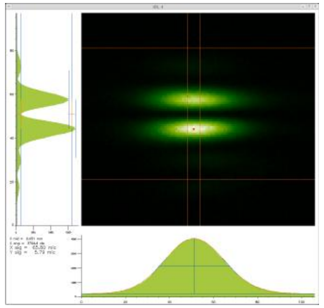


Finite vert. beam size ==>

Non-zero central intensity

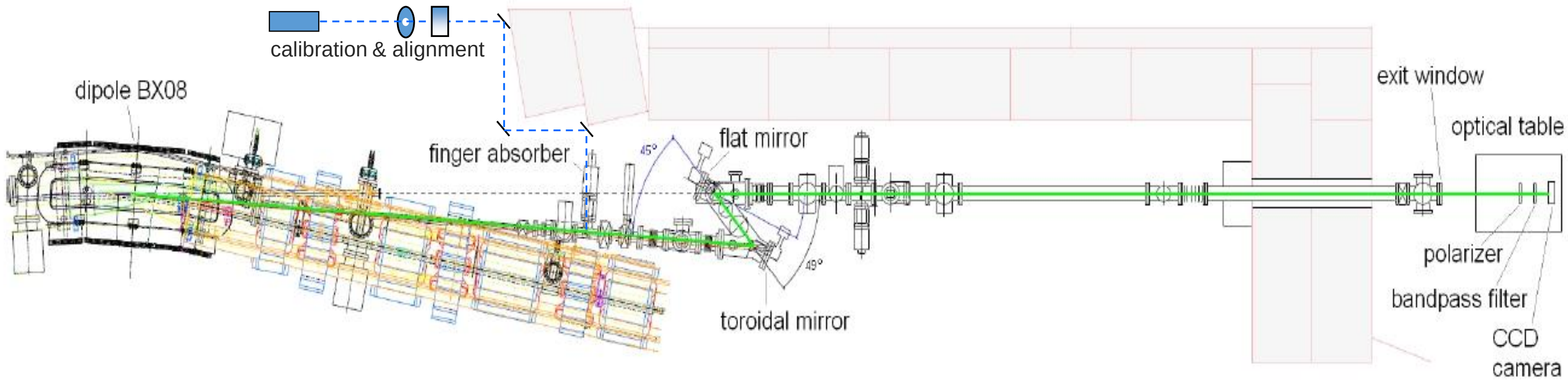
Synchrotron Radiation Monitors: SLS π-Polarization Monitor





- operating wavelength: variable (266 nm)
- opening angle: 7 mrad_H x 9 mrad_V
- finger absorber to block main SR intensity
- π-polarization or interferometric method selectable

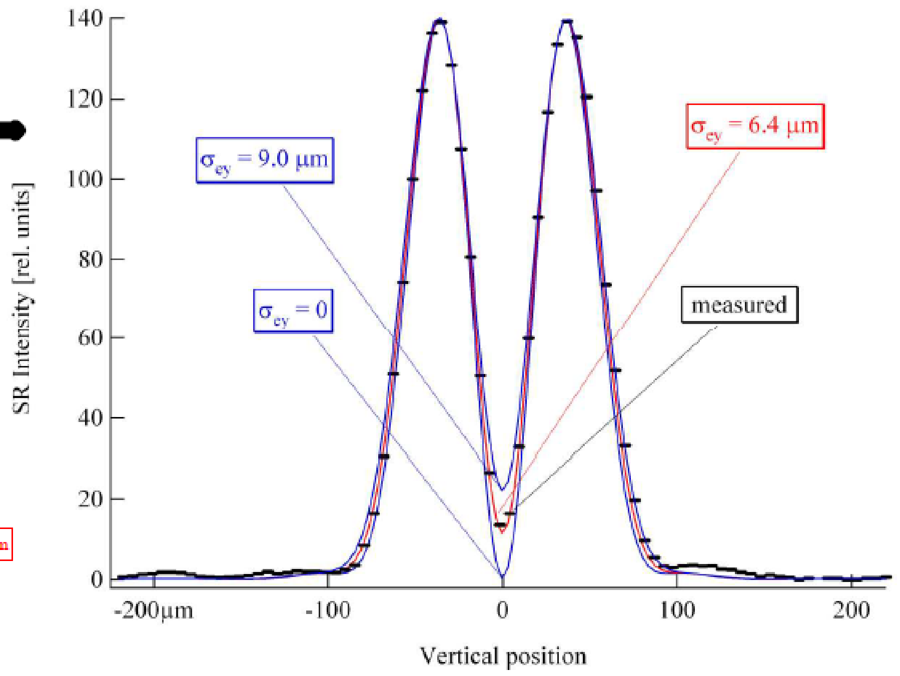
- imaging by toroidal mirror
- magnification: 1.453
- surface quality of optics: < 20 nm (λ/30 @ 633 nm)

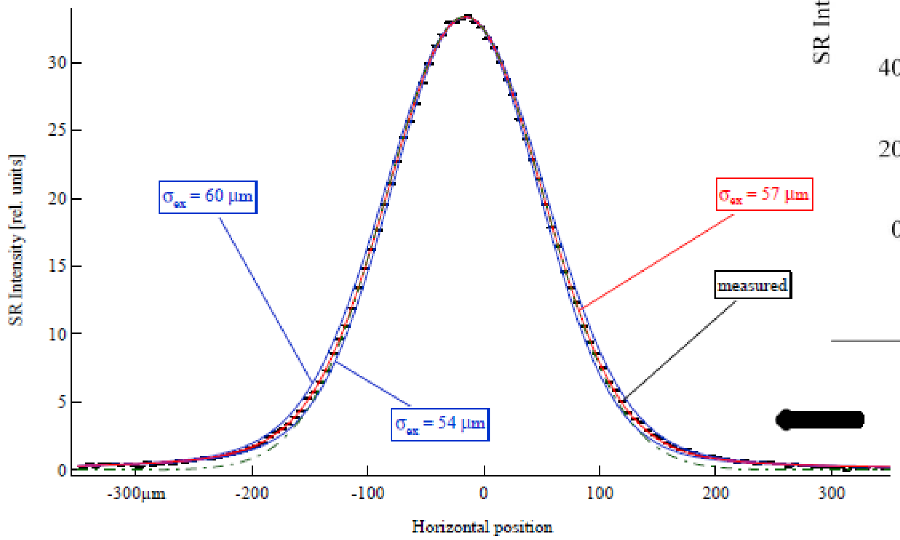


SLS: vertical beam size σ_y = 3.6 µm ± 0.6 µm for β_y = 13.5 m → vertical ε_y = 0.9 pm (natural limit from 1/γ: $\varepsilon_{y,min}$ = 0.2 pm)

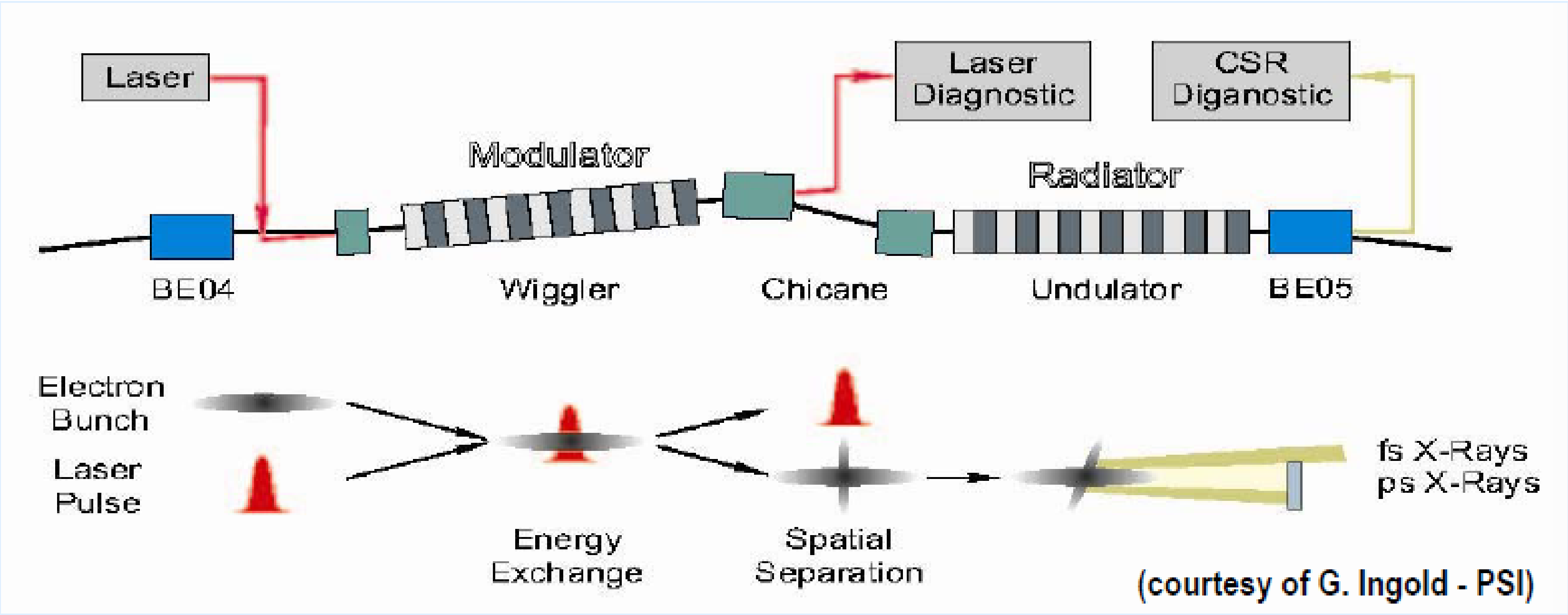
Vertical: Predicted profiles (SRW*) for beam height values 0, 6.4, 9.0 µm, and measured.
Statistical rms error = 0.1µm

*) Chubar et al.

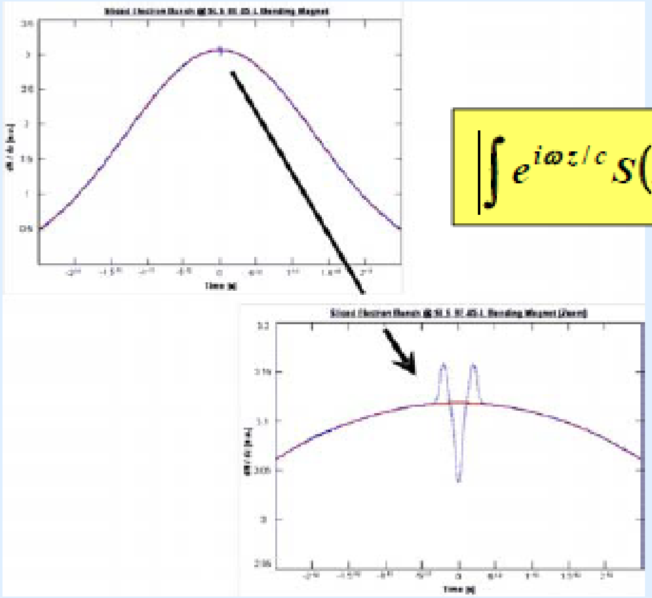




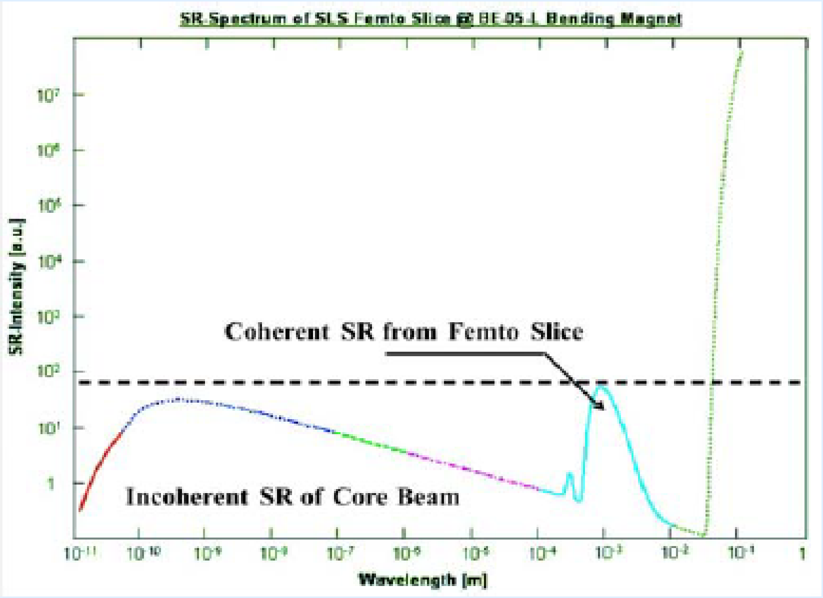
Horizontal: Predicted profiles (SRW) for beam width values 54, 57, 60 µm, and measured.
Statistical rms error = 0.3µm



FEMTO-Bunch Slicing in SLS Storage Ring…:



$$\left|\int e^{i\omega z/c}\, S(z)\, dz\right|^2$$



SLS Operation Statistics

Beam Time Statistics	2017		2016	
Total beam time	6784 h	77.4%	6864 h	78.1%
• user operation	5048 h	57.6%	5016 h	57.1%
- incl. compensation time	184 h	2.1%	160 h	1.8%
• beamline commissioning	792 h	9.0%	800 h	9.1%
• setup + beam development	944 h	10.8%	1048 h	11.9%
Shutdown	1976 h	22.9%	1928 h	21.9%
User operation downtimes	30		25	
• unscheduled outage duration	63 h	1.3%	45 h	0.9%
• injector outage (non top-up)	1 h	0.0%	1 h	0.0%
Total beam integral	2528 Ah		2497 Ah	
Availability	98.7%		99.1%	
Availability after Compensation	102.5%		102.4%	
MTBF	163 h		193 h	
MTTR (mean time to recover)	2.1 h		1.8 h	
MTBD (mean time between distortions)	42 h		67 h	

Upgrade plan: SLS-2

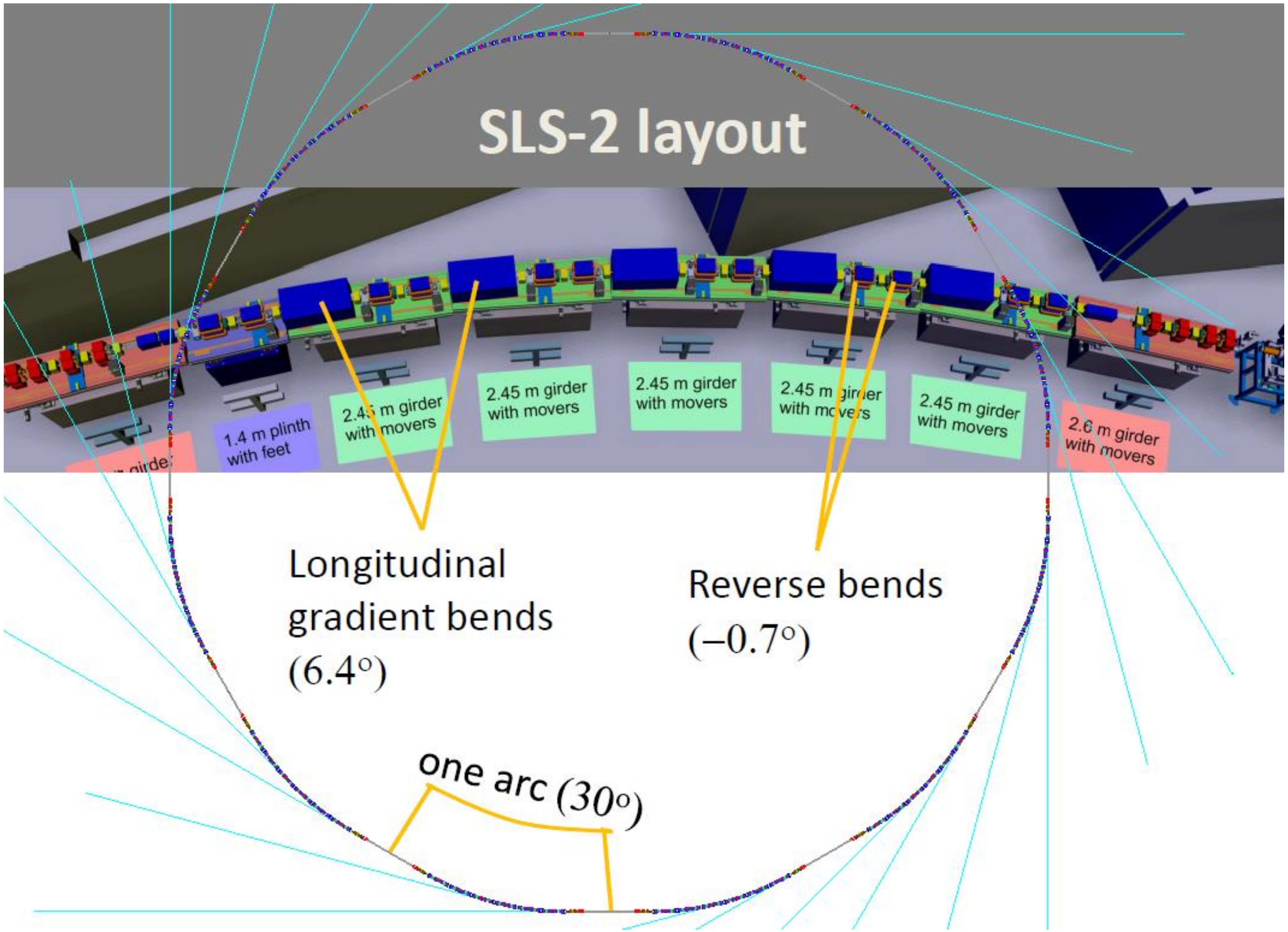
SLS upgrade task: $\varepsilon_x = 5$ nm $\rightarrow \varepsilon_x < 150$ pm

SLS upgrade challenge: small circumference

- Scaling $\varepsilon_x \propto (\text{Energy})^2 / (\text{Circumference})^3$
- Scaling other designs to SLS ⇨ not competitive ✘
  - Scaling MAX-IV, ESRF-EBS, SIRIUS etc. $\rightarrow \varepsilon_x > 500$ pm
- No space for very many lattice cells (MBA)
- No space for damping wigglers

⇨ New lattice concept for SLS-2 $\varepsilon_x \rightarrow$ **125 pm**

SLS-2 layout



1.4 m plinth with feet
2.45 m girder with movers
2.45 m girder with movers
2.45 m girder with movers
2.6 m girder with movers
Longitudinal gradient bends (6.4°)
Reverse bends (–0.7°)
one arc (30°)

Cyclotrons

The Classical Cyclotron

two capacitive electrodes „Dees“, two gaps per turn

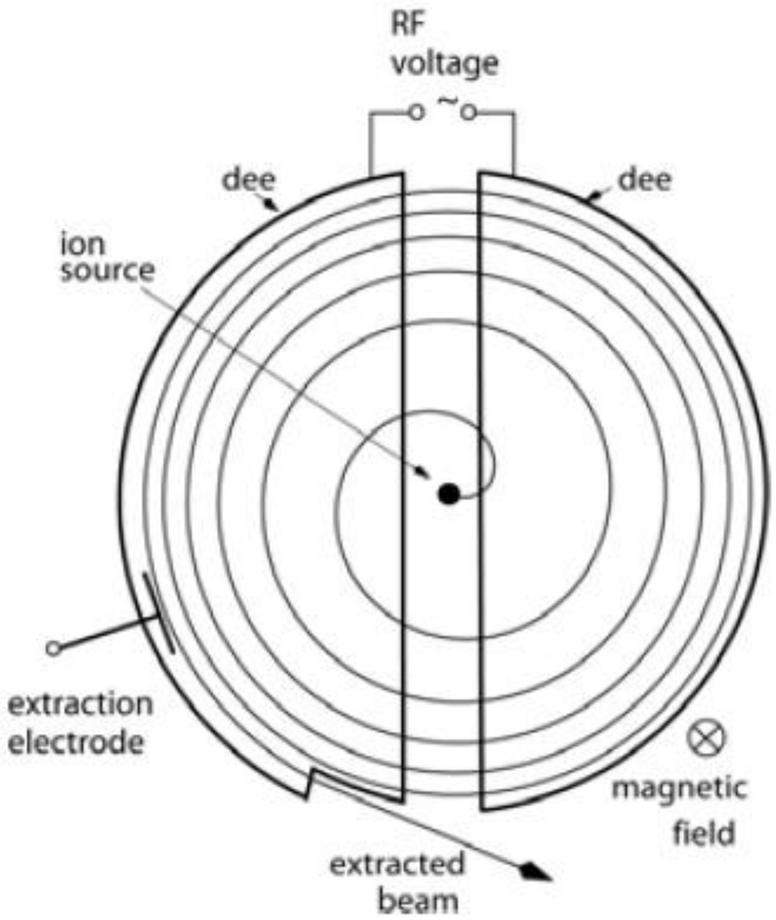
internal ion source

homogenous B field

constant revolution time

(for low energy, $\gamma \approx 1$)

$$\omega_c = \frac{eB_z}{m}$$



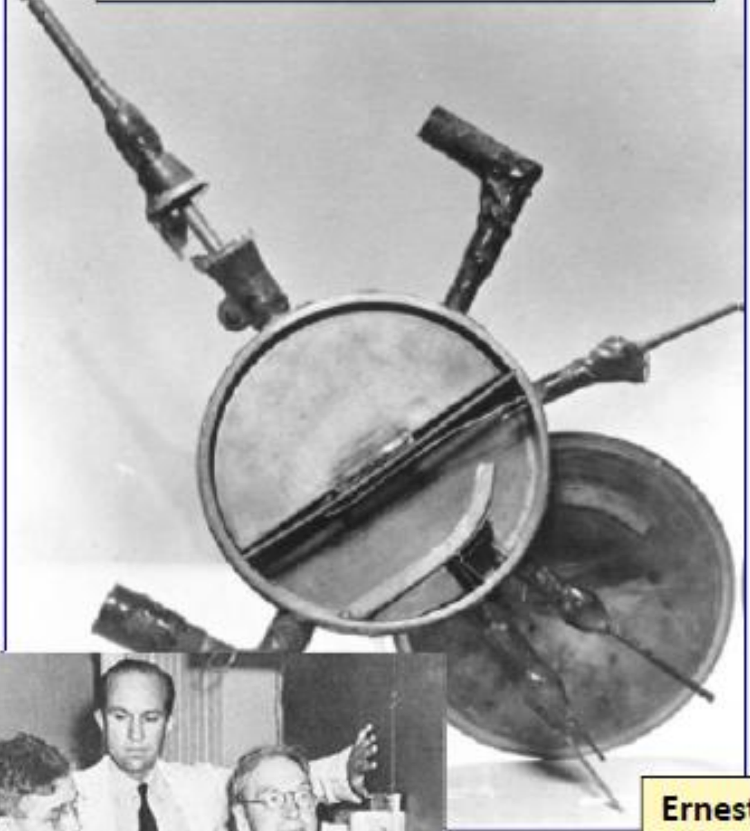
powerful concept:

→ **simplicity, compactness**

→ **continuous injection/extraction**

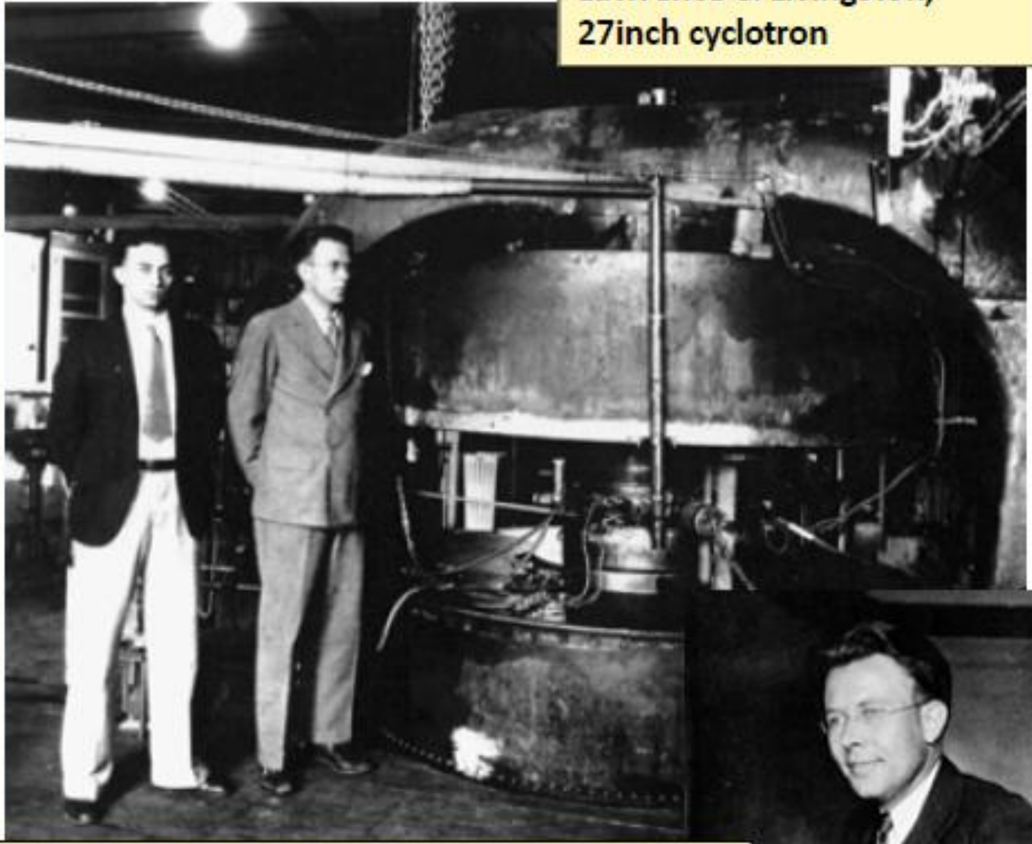
→ **multiple usage of accelerating voltage**

some history …



first cyclotron: 1931, Berkeley

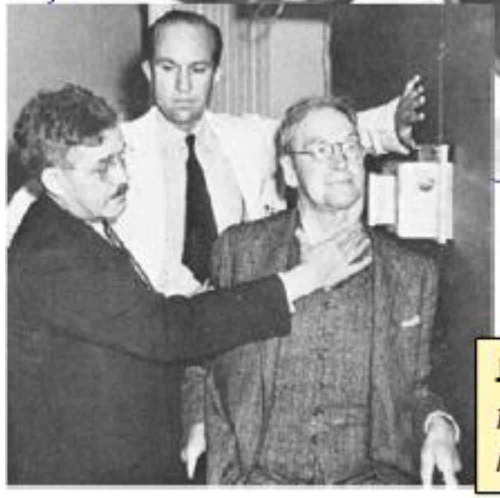
1kV gap-voltage 80keV protons



Lawrence & Livingston, 27inch cyclotron

Ernest Lawrence, Nobel Prize 1939

"for the invention and development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements"



John Lawrence (center), 1940'ies

first medical applications: treating patients with neutrons generated in the 60inch cyclotron

isochronicity and scaling

- **cyclotron frequency** (homogeneous) B-field:

$$\omega_c = \frac{eB}{\gamma m_0}$$

- magnetic rigidity:

$$B \cdot R = \frac{p}{e} = \beta\gamma \frac{m_0 c}{e}$$

- orbit radius from isochronicity:

$$R = \frac{c}{\omega_c}\beta = R_\infty \beta$$
$$= \frac{c}{\omega_c}\sqrt{1-\gamma^{-2}}$$

- since $R \propto \beta;\ \ B \cdot R \propto p \propto \beta\gamma$

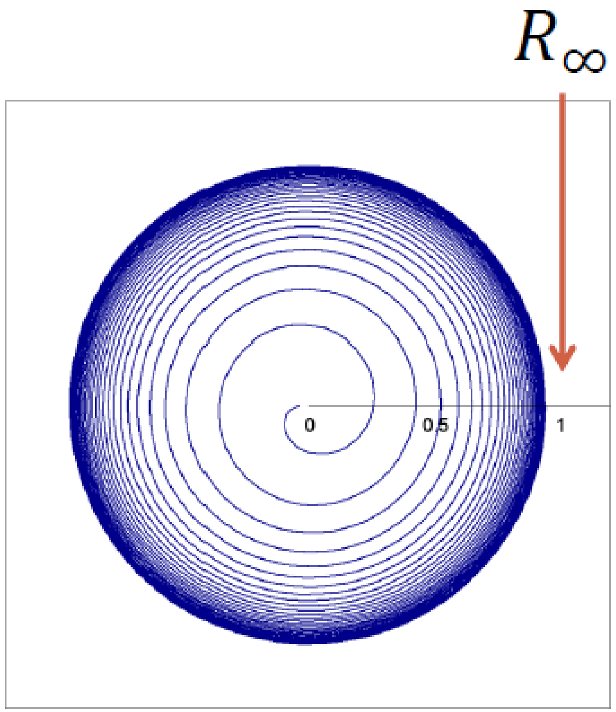
$$\rightarrow B \propto \gamma$$

- turn number:

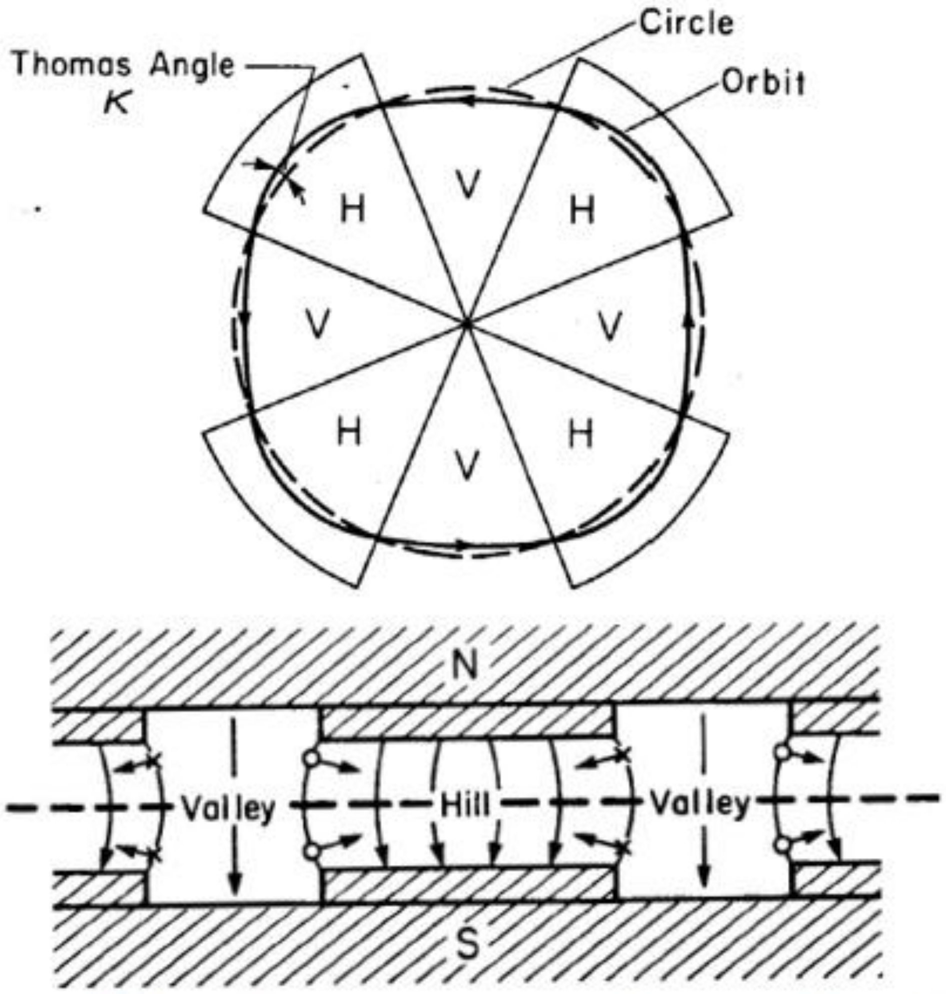
$$n_t = \frac{m_0 c^2}{U_t}(\gamma - 1)$$

energy gain per turn

radius increment per turn decreases with increasing energy because the revolution time must stay constant
→ extraction becomes more and more difficult at higher energies



Thomas focusing (1938)



A radial-sector cyclotron, showing orbit scalloping and the Thomas focusing at the sector edges.

Make **B** azimuthally dependent

↓

Radial (Separated) Sector Cyclotrons

Focusing in sector cyclotrons

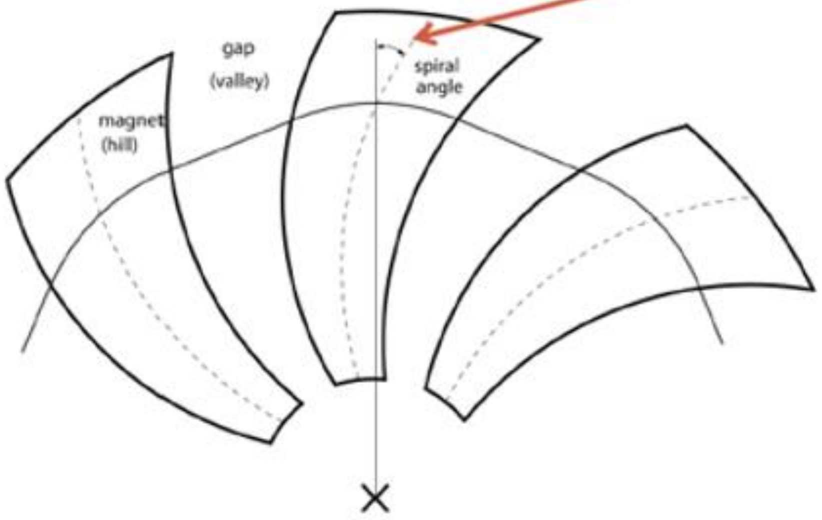
- hill / valley variation of magnetic field (Thomas focusing):

  Flutter factor: $F = \frac{\overline{B_z^2} - \overline{B_z}^2}{\overline{B_z}^2}$

  vertical betatron n.: $\nu_z^2 = -\frac{R}{B_z}\frac{\partial B_z}{\partial R} + F$

- with additional spiral angle of bending field:

$$\nu_z^2 = -\frac{R}{B_z}\frac{\partial B_z}{\partial R} + F(1 + 2 \cdot \tan^2 \delta)$$

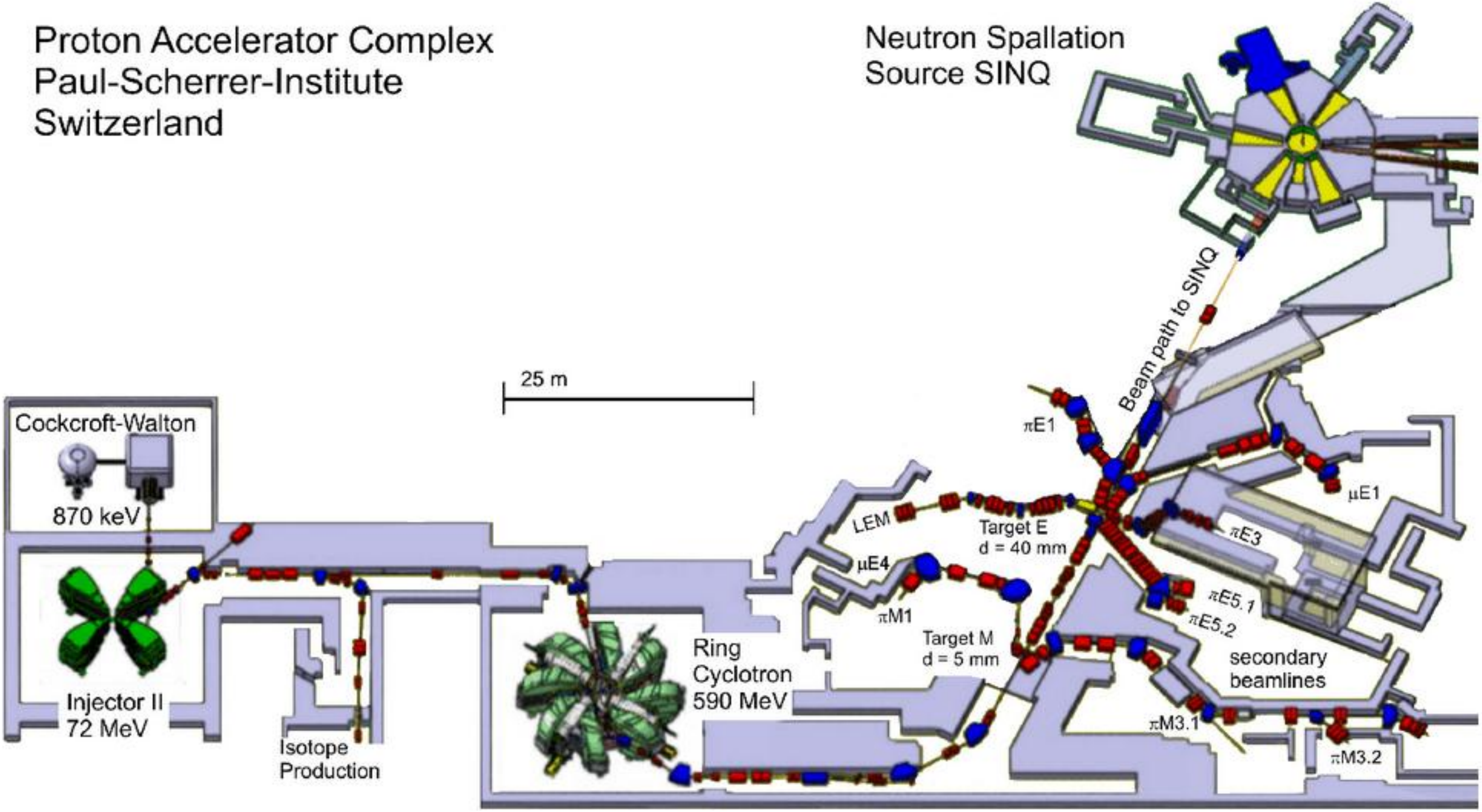


Separated Sector Cyclotrons

- **edge+sector focusing**, i.e. spiral magnet boundaries, azimuthally varying B-field
- **modular layout,** larger cyclotrons possible, sector magnets, box resonators
- **external injection** required, i.e. pre-accelerator
- **radially wide vacuum chamber**; inflatable seals etc.
- detailed **field shaping for focusing and isochronisity** required
- strength: **CW acceleration**; higher energy up to 1GeV, high **extraction efficiency** possible:

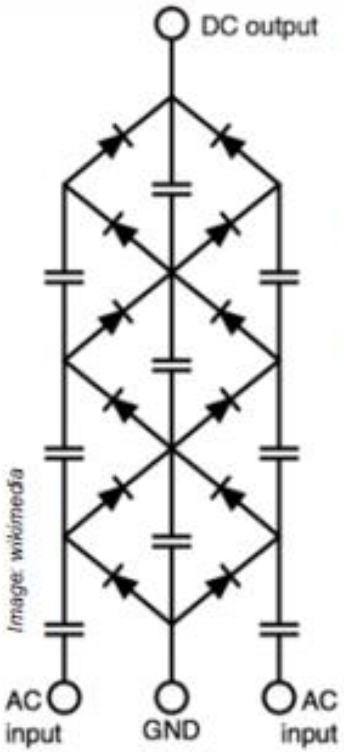
  e.g. PSI: 99.98% = $(1 - 2 \cdot 10^{-4})$

High Intensity Proton Accelerator (HIPA) complex at PSI



Proton Accelerator Complex
Paul-Scherrer-Institute
Switzerland
Neutron Spallation
Source SINQ
Beam path to SINQ
25 m
Cockcroft-Walton
870 keV
Injector II
72 MeV
Isotope
Production
Ring
Cyclotron
590 MeV
πE1
μE1
LEM
Target E
d = 40 mm
πE3
μE4
πM1
Target M
d = 5 mm
πE5.1
πE5.2
secondary
beamlines
πM3.1
πM3.2

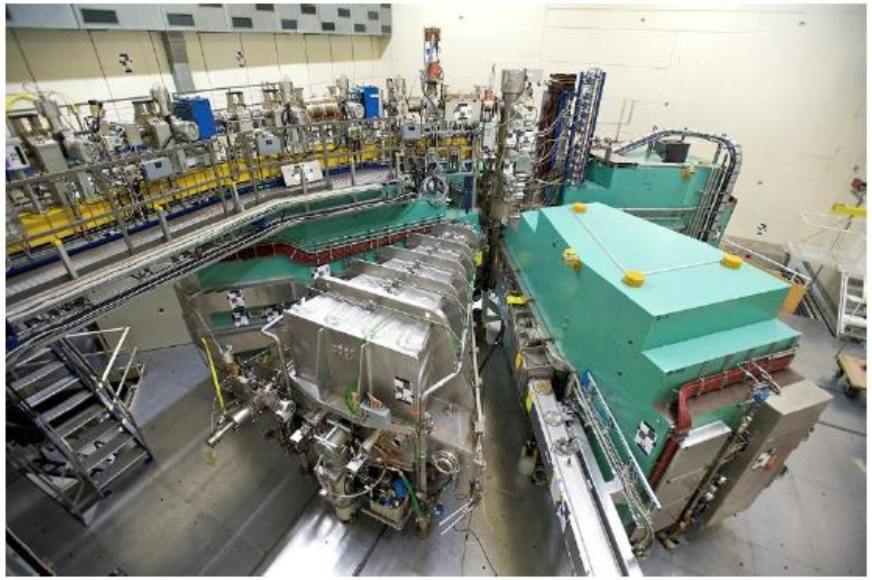
Cockcroft-Walton accelerator



- Concept: Rectifying diodes shift up voltage offset on a capacitor chain (staircase)
- Can reach up to a few MeV
- Invented by J.D. Cockcroft and E.T.S. Walton (1932)
- Main applications:
  - injectors for high-energy, high-intensity accelerators (but more and more replaced by RF quadrupoles)

Cockcroft-Walton injector at PSI (870 keV)

The Injector cyclotron



Injection energy: 870 keV
Extraction energy: 72 MeV
Number of turns: 83

Resonator	type	material	frequency	gap voltage	Wall losses in cavity	incident power @ 2.4 mA Beam
1 & 3	Double gap cavity	aluminum	50 MHz	~ 420 kVp (kV peak)	~ 150 kW	~ 225 kW
2 & 4	Flattop cavity	aluminum	150 MHz	~ 31 kVp	~ 5 kW	~ 14 kW
2 & 4 new	Single gap cavity	aluminum	50 MHz	~ 400 kVp @ extraction	~ 50 kW	~ 100 kW

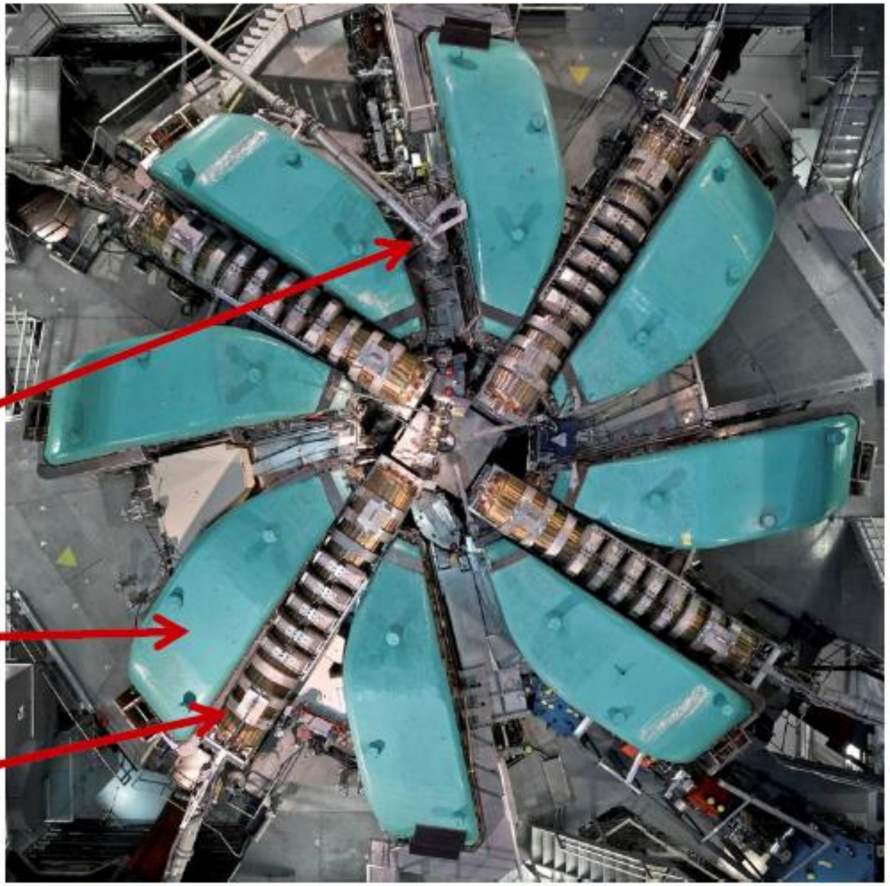
The Ring cyclotron

Injection energy: 72 MeV
Extraction energy: 590 MeV
Number of turns: 186

Flattop cavity

Sector magnet

Copper cavity



numbers	type	material	frequency	gap voltage	Wall losses in cavity	incident power @ 2.4 mA beam
4	Main cavity	copper	50 MHz	~ 850 kVp	~ 250 kW	~ 600 kW
1	Flattop cavity	aluminum	150 MHz	555 kVp	~ 90 kW	~ - 30 kW

PSI basic cyclotrons

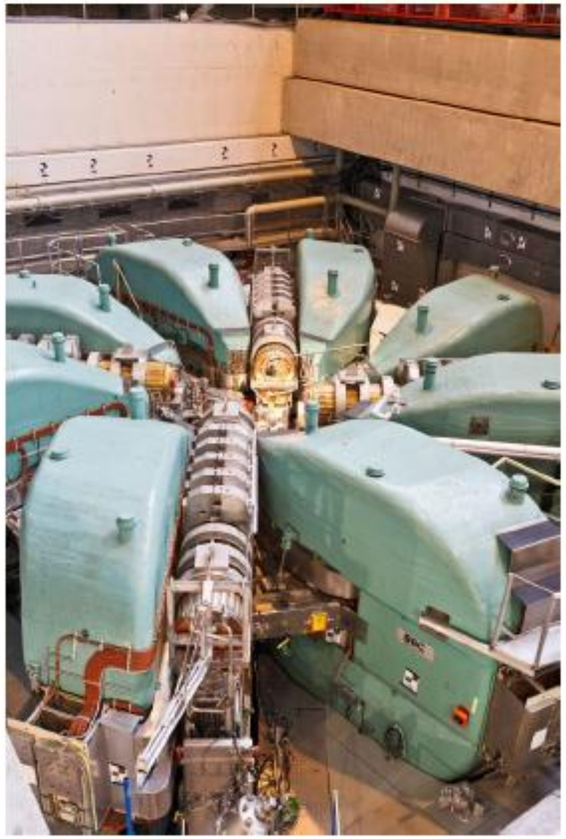
	PSI Ring	**INJECTOR II**
particles	p	p
K [MeV]	592	72
magnets (poles)	8	4
peak field strength [T]	2.1	0.4
R_{inj}/R_{extr} [m]	2.4/4.5	0.4/3.5
P_{max} [kW]	1300	160
extraction efficiency (tot. transmission)	0.9998	0.9998
extraction method	electrostatic deflector	electrostatic deflector
comment	high intensity	high intensity

Sector magnets

- cyclotron magnets typically cover a wide radial range $\rightarrow$ magnets are heavy and bulky, thus costly

PSI sector magnet

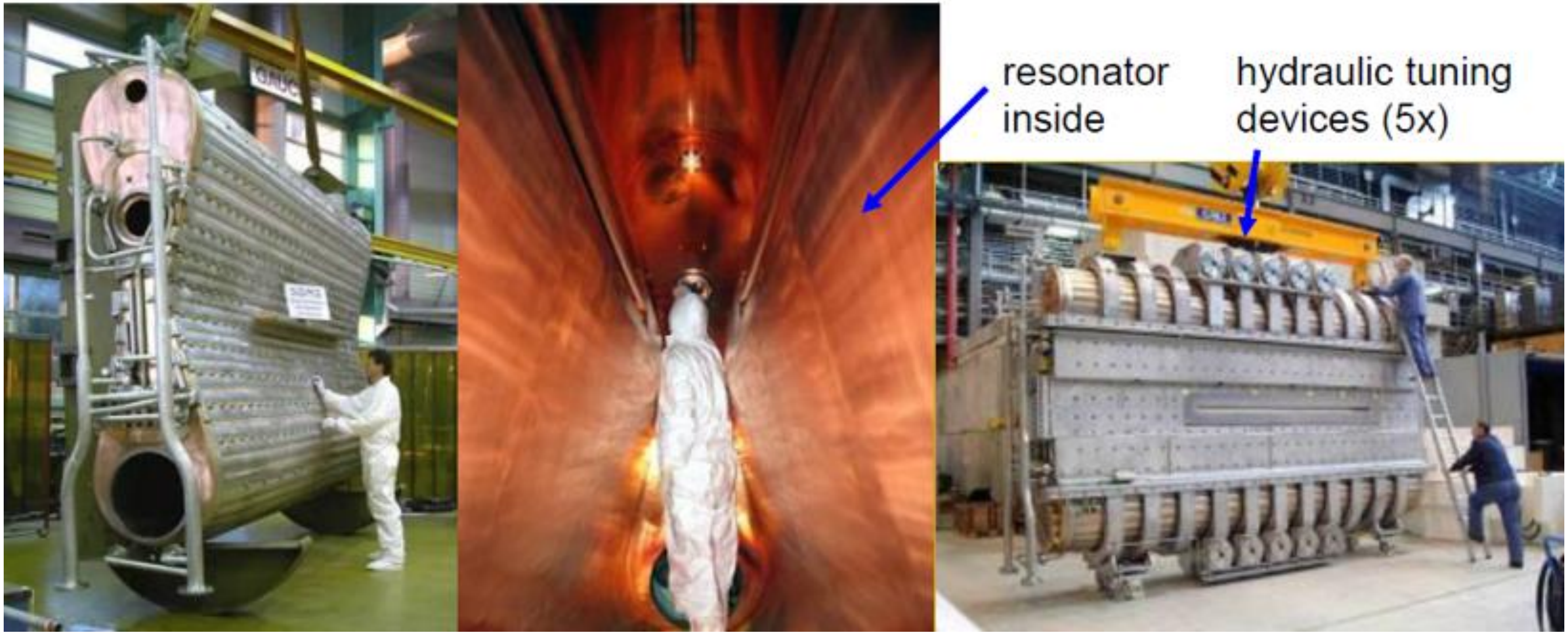
iron weight: 250 tons
coil weight: 28 tons
orbit radius: 2.1…4.5 m
spiral angle: 35 deg



Copper resonators in operations of PSI Ring cyclotron

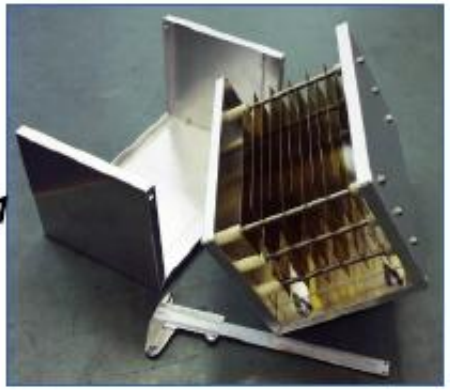
- **f = 50.6MHz; Q_0 = 4,8·10^4; U_{max}=1.2MV**

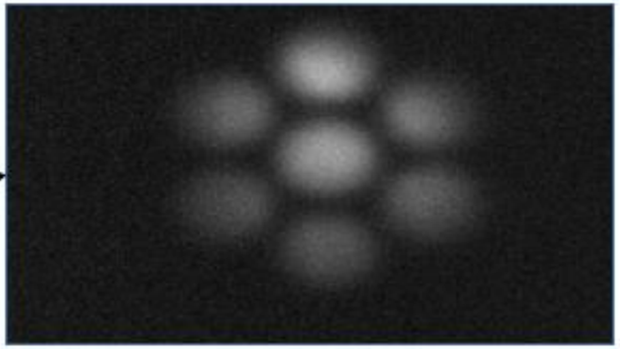
- transfer of up to **400kW power to the beam** per cavity



HIPA Operational Facts

- 1.3 MW proton beam with $\sigma_x = \sigma_y \approx 1$ mm [→ TM and TE regions] melts beam pipe in **≈ 10 ms**
- MPS based on ca. 150 interconnected very fast (<100μs) VME modules treating about **1500 signals**
- PSI MPS can generate a **beam interlock in < 5 ms**
- MPS gets signals from:
  - Magnet power supplies
  - BPMs
  - Beam loss monitors (110 ion chambers)
  - Current monitors (beam transmission)
  - Halo monitors
  - Temperature sensors (collimators)
  - VIMOS tungsten mesh (SINQ beam footprint)





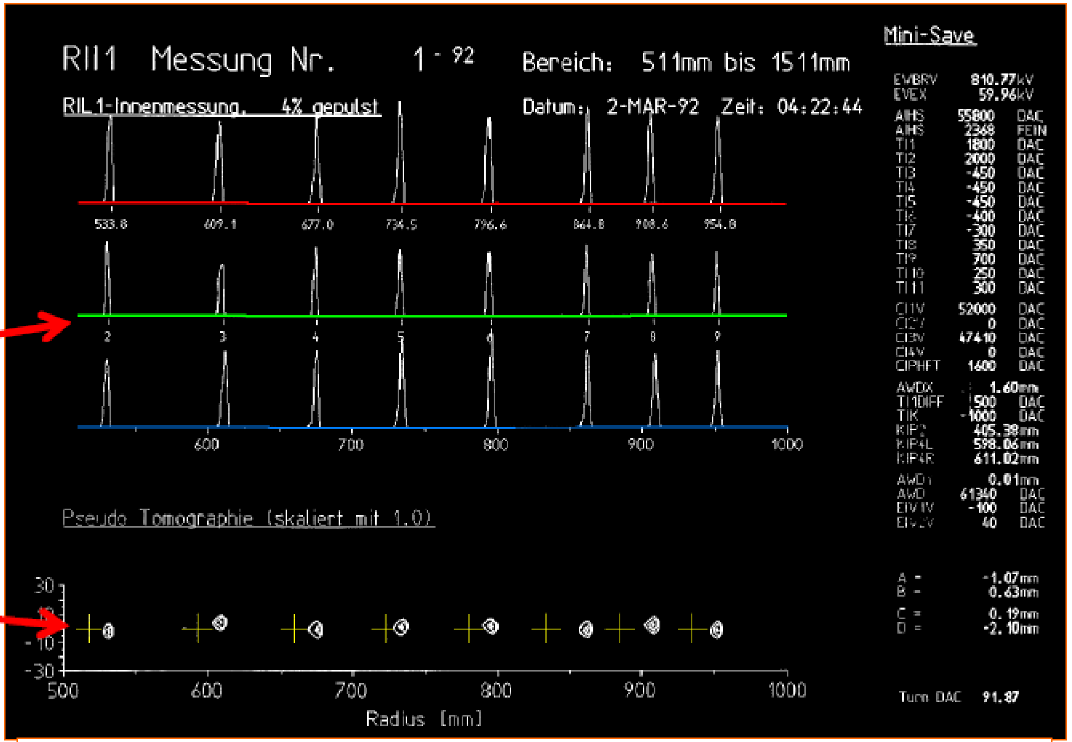
Instrumentation: radial probe for turn counting / orbit analysis

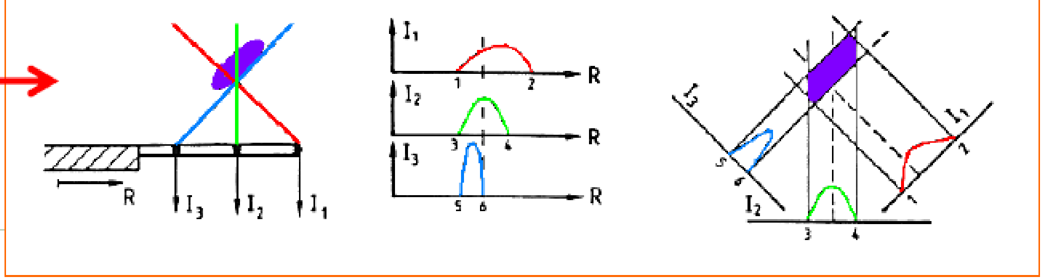
wire scanner with three tilted wires delivers radial beam profile and some vertical information

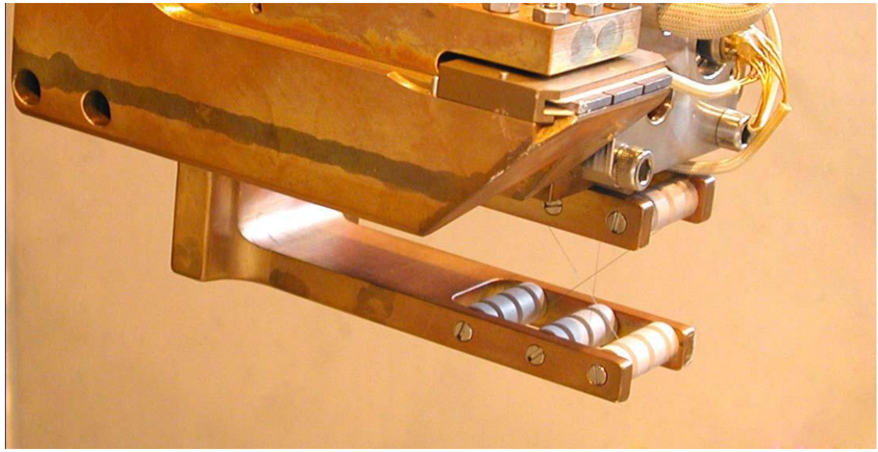
radial: positions of individual turns

vertical/radial orbit positions and stored reference orbit (crosses)

«pseudo tomography» with tilted wires



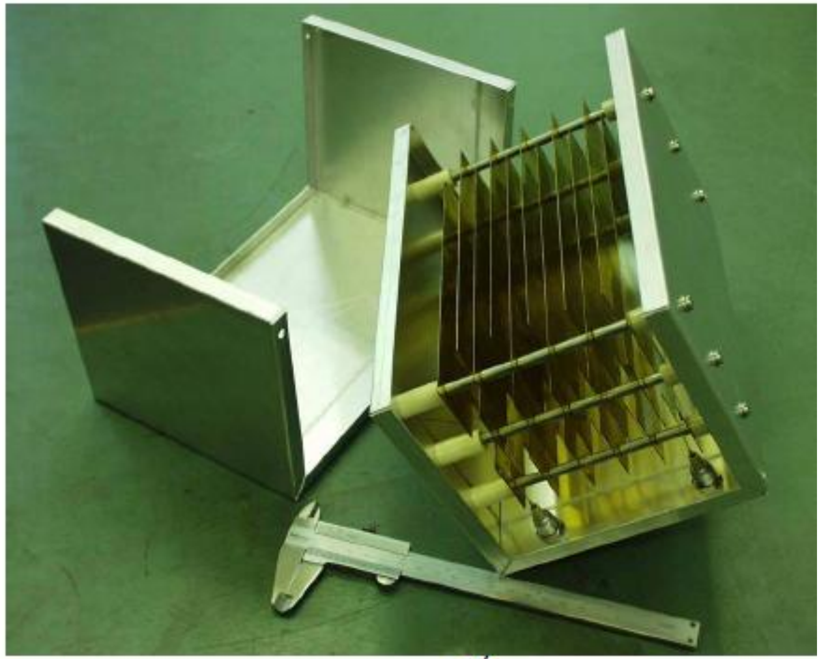


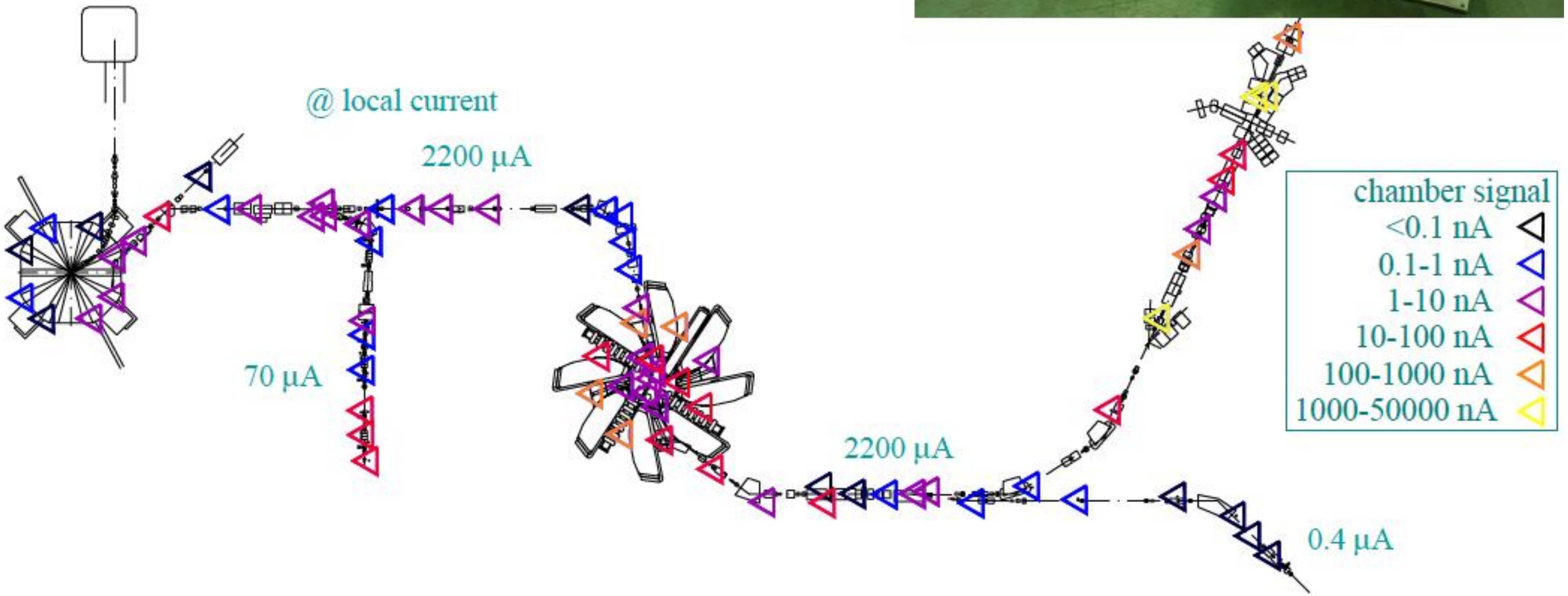


Beam loss monitors

- ionization chambers (ambient air filled, 300 V)

- useful at beam energies >40 MeV → proton range in steel > 3 mm
- placed ~0.1...1 m from beam, fixed position for reproducibility
- approximate calibration by steering low current beam into wall





Beam losses: „protection aspect“

- melting of cyclotron components - missteered beam
- fast interlock generation needed (~1 ms)
- prevent activation

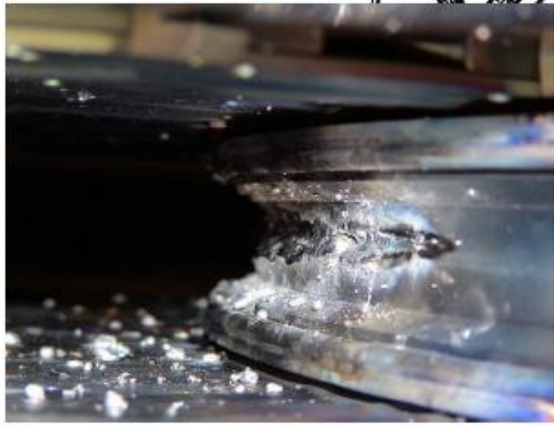
collimators

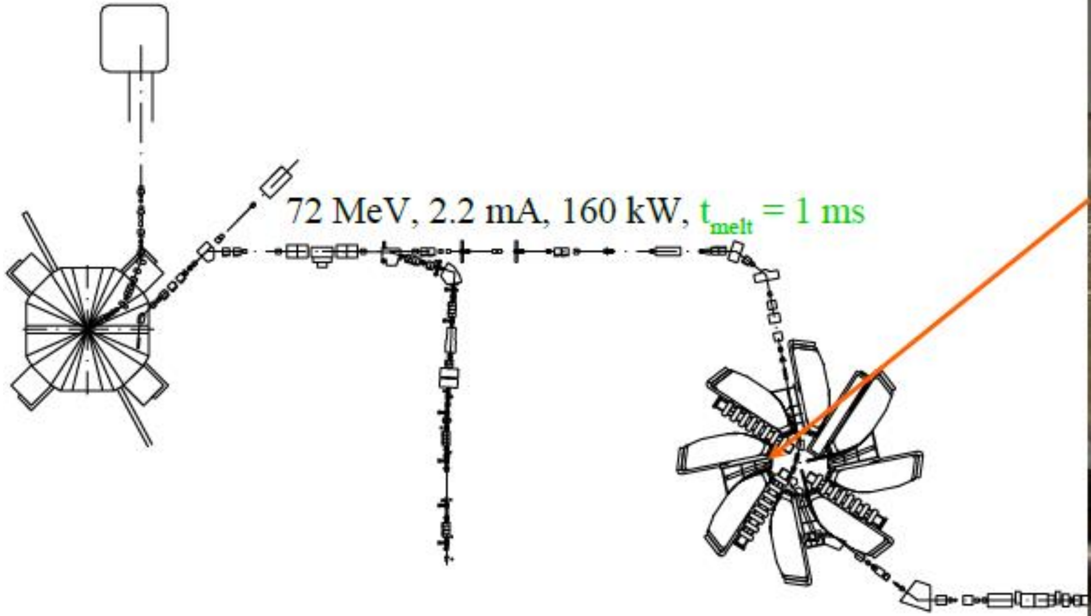
with current readout

injection into Ring cyclotron:

collimator and coil support destroyed

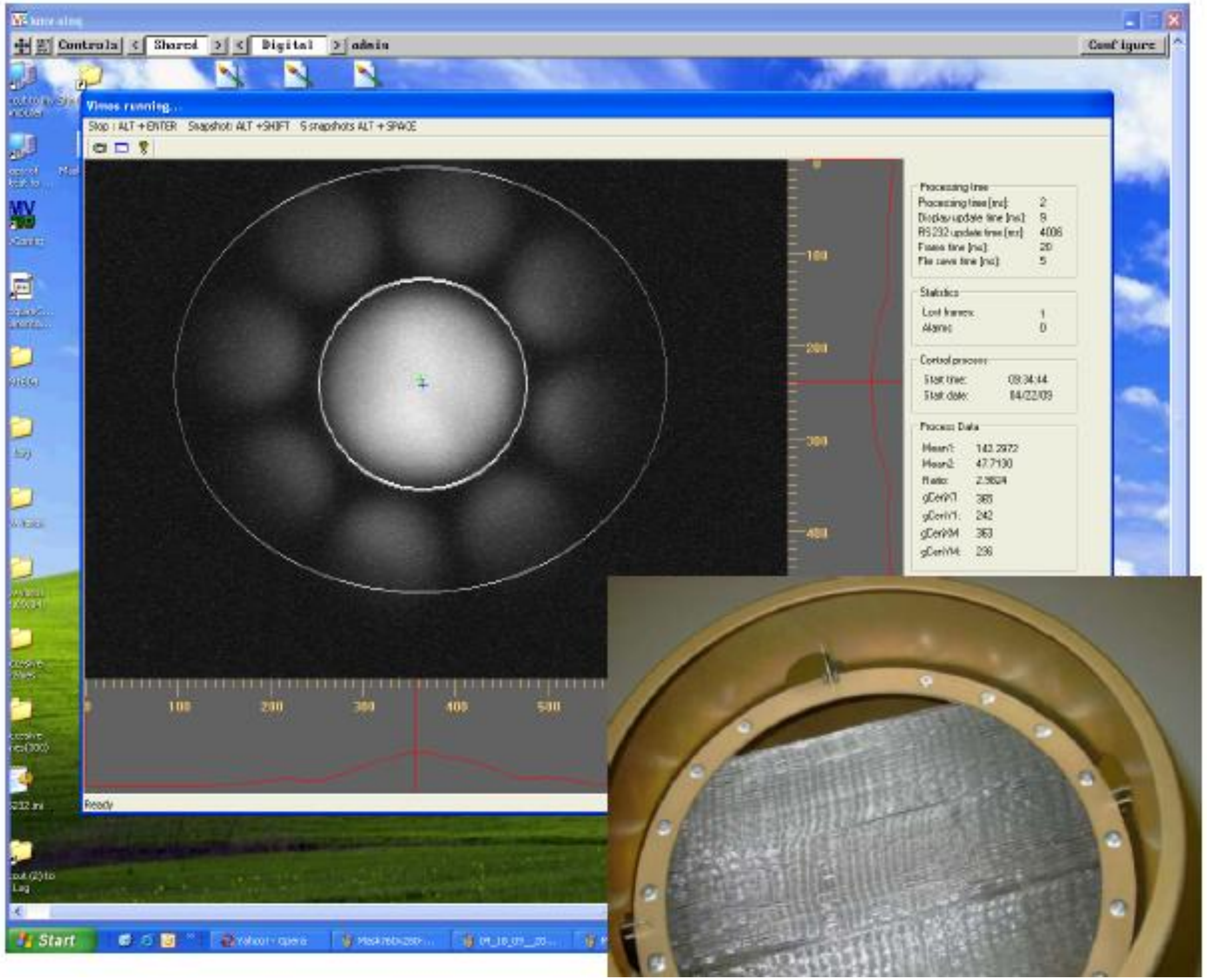
(defect of high level interlock module)





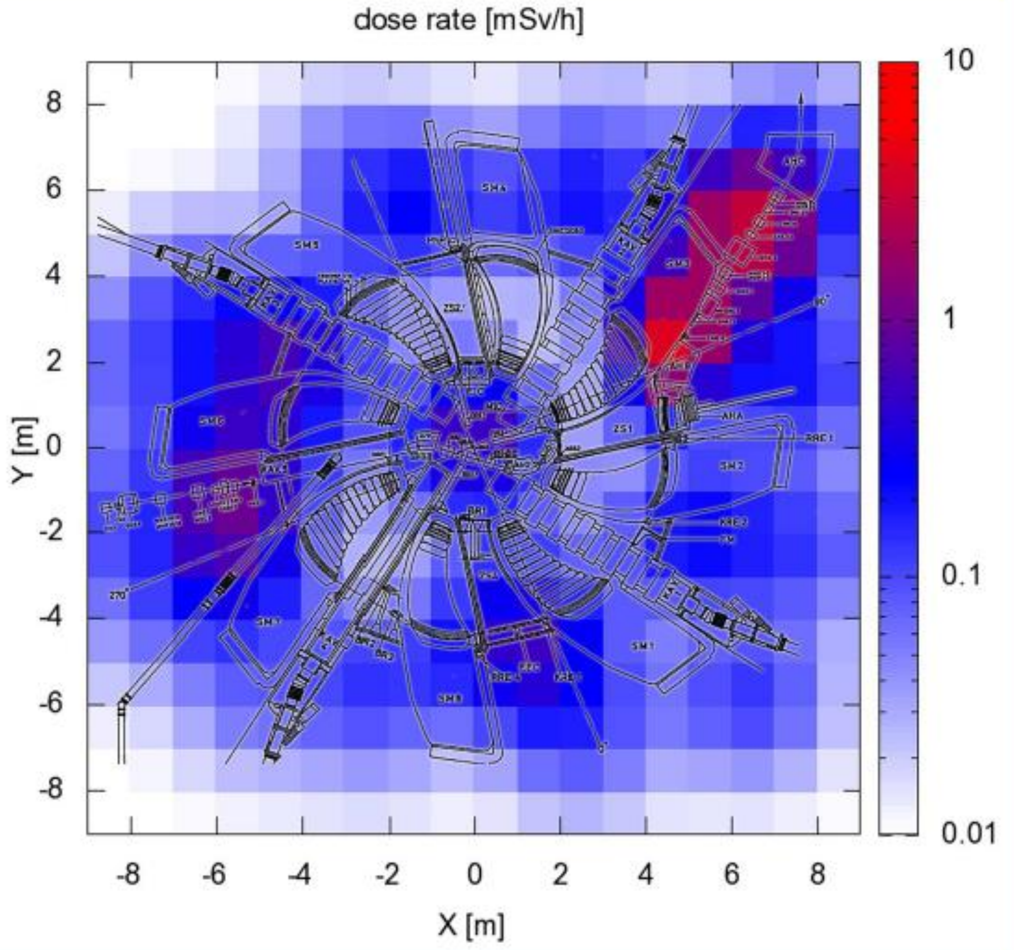
Tungsten Grid located 40 cm upstream of the SINQ Target visualized by optic-fibers and camera gives an image of the thermal radiation

- VIMOS image is digitized to detect abnormal irradiation condition (overfocusing and/or missteering)
- 50 frames / second
- If 4 subsequent frames deviate from thresholds an interlock signal is sent
- Deviation is calculated through intensity ratios and absolute maximum values.



Losses and resulting activation in PSI Ring

- maximum intensity is limited by losses (typ. 200-400nA) and **activation**
- losses at extraction dominate the activation
- thus efforts at optimizing performance are concentrated on the extraction
  → **largest possible turn separation; design of electrostatic septum**



activation level allows for necessary service/repair work

- personnel dose for typical repair mission 50-300μSv
- optimization by adapted local shielding measures; shielded service boxes for exchange of activated components
- detailed planning of shutdown work

example (2010):
personnel dose for 3 month shutdown:

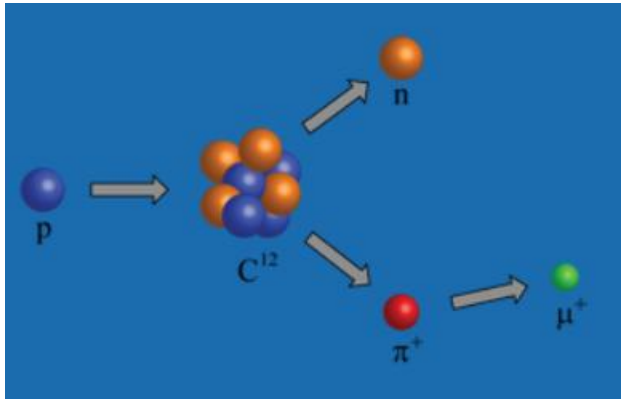
47mSv, 186 persons
max per person: 2.9mSv

map interpolated from ~30 measured locations

HIPA Operation Statistics

Beam-time statistics for HIPA	2017
Total scheduled user beam time	**4838 h**
Beam current integral • to meson production targets • to SINQ • to UCN • to isotope production targets	 7.97 Ah 4.10 Ah 0.064 Ah 0.013 Ah
Outages: current < 1 mA, time > 5 min	228 h
Availability	93.1 %

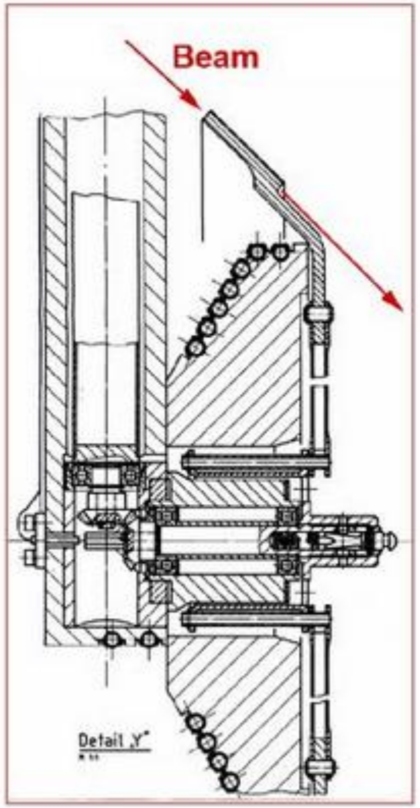
Swiss Muon Source (SμS)



- the world's most intense continuous beam muon source

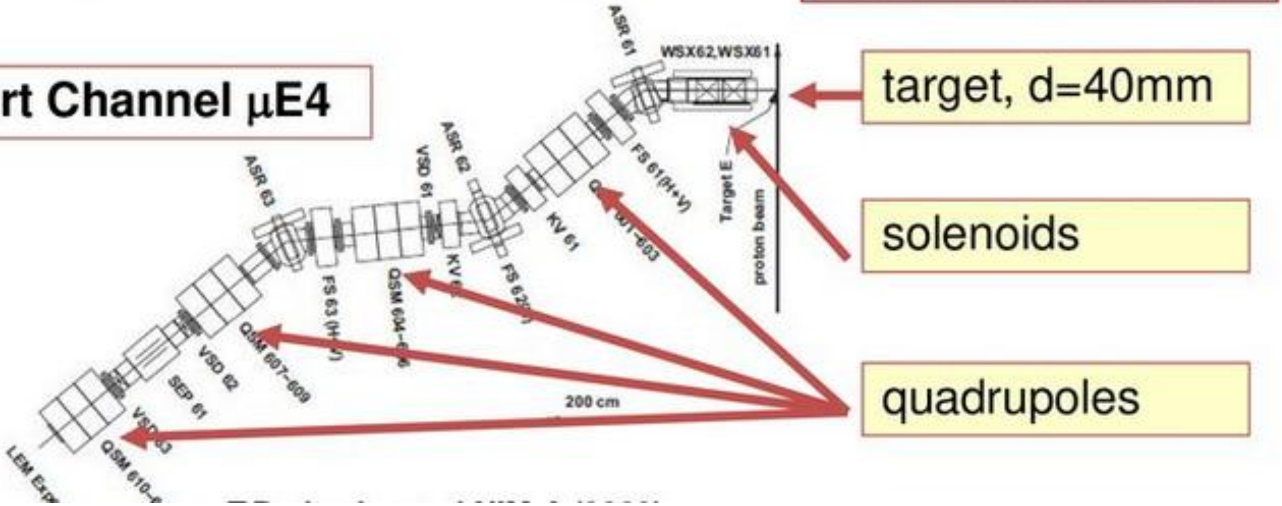
- one of the main applications of these intense muon beams is muon spin spectroscopy

Meson Production Target

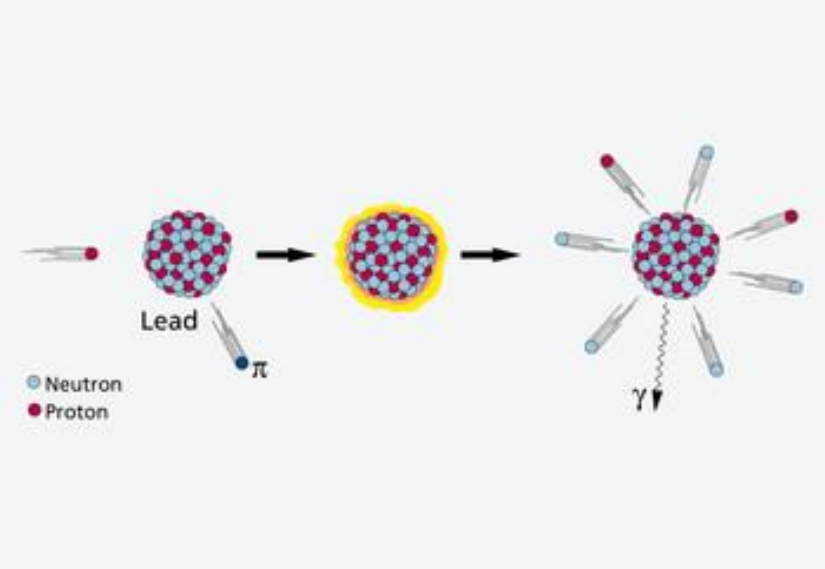


TARGET CONE	
Mean diameter:	**450 mm**
Graphite density:	1.8 g/cm^3
Operating Temp.:	**1700 K**
Irrad. damage rate:	0.1 dpa/Ah
Rotation Speed:	**1 Turn/s**
Target thickness:	**40 mm**
	7 g/cm^2
Beam loss:	12 %
Power deposit.:	20 kW/mA

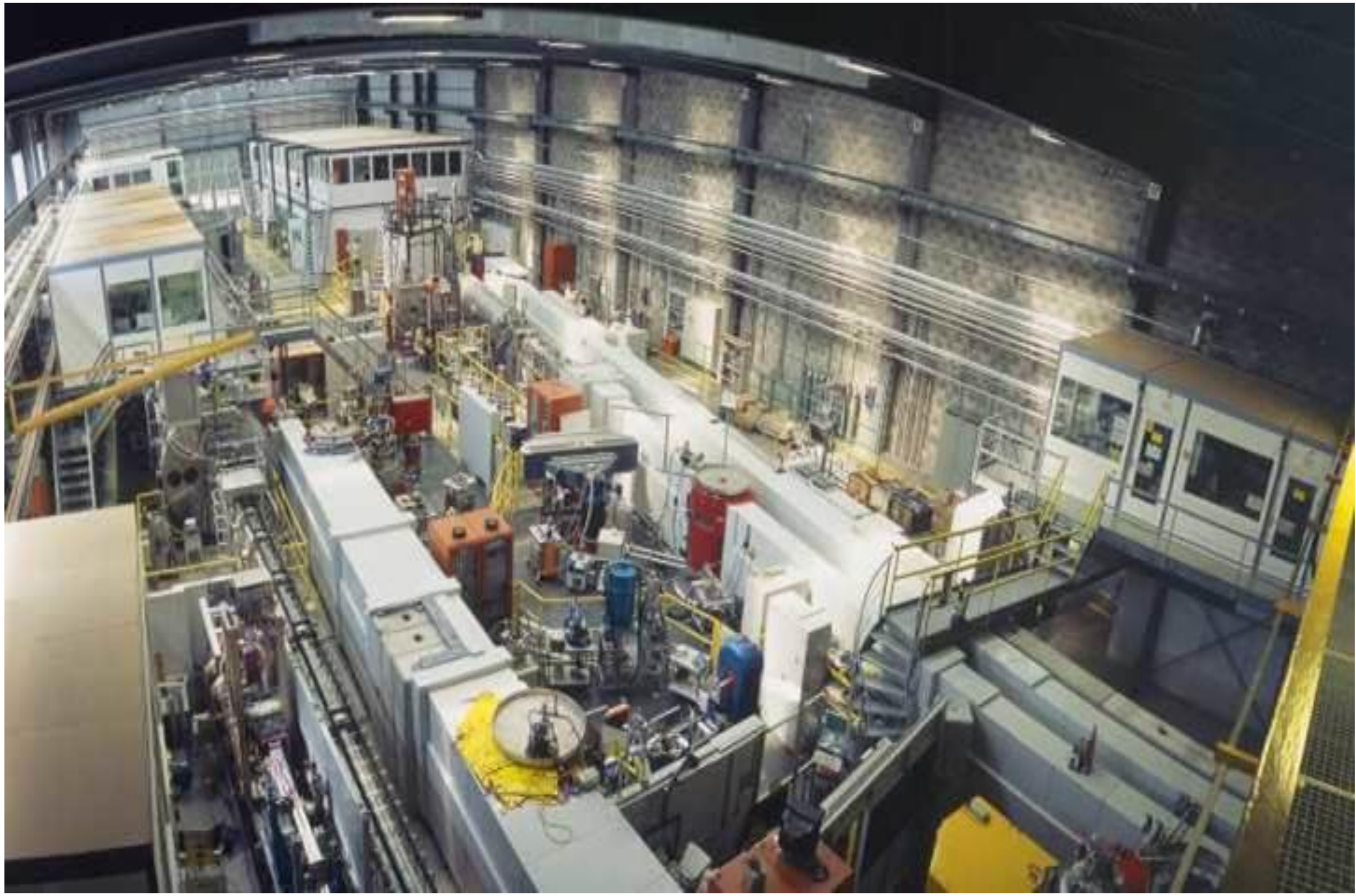
Muon Transport Channel μE4



Muon Rate:
4.6E8 μ$^+$/sec
@ p=29.8 MeV/c



Swiss Spallation Neutron Source (SINQ)



- a continuous neutron source – the first of its kind in the world – with a flux of about 10^{14} n/cm^2/s.

- research in solid state physics and chemistry, materials science, biology, medicine, environmental science

- increasing number of industrial applications

References/Acknowledgements

V. Schlott, V. Arsov, R. Ischebeck, S. Reiche, L. Rivkin, B. Keil, F. Frei, C. Ozkan, F. Müller, F. Frei, S. Hunziker, M. Aiba, A. Streun, M. Kaiser, F. Löehl, H. Braun, T. Garvey, R. Dölling, S. Borelli, L. Frölich, B. Steerenberg, B. Nash, G. Ingold, W. Joho, and many others.


Thank You!