PITZ Overview

High brightness electron sources and their applications

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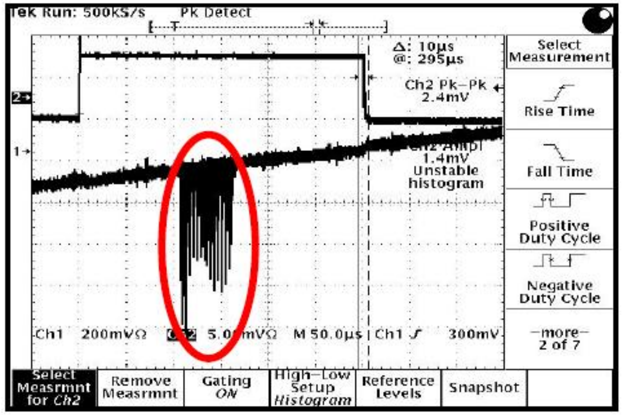
Photo Injector Test Facility at DESY in Zeuthen (PITZ)

What? When? Why?

- Develop and optimise electron sources for the X-ray lasers and particle accelerators of the future like FLASH & EuXFEL

23 Years ago: Start of beam operation at PITZ

January 13th, 2002:
First photo electrons at PITZ



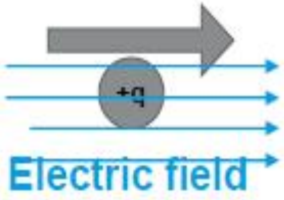
Official start on 30.1.2002: Prof. Wagner and Prof. Wanka open the photo cathode laser shutter during the colloquium „10 years DESY in Zeuthen"

Motivation

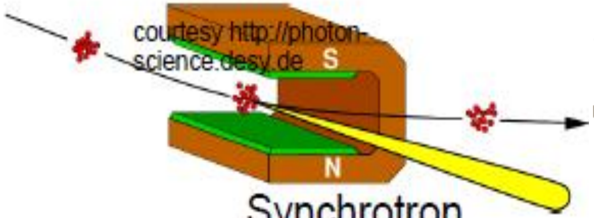
Accelerator, Light Source and Applications

Accelerators produce extremely bright, tunable beams (X-rays, IR, THz, etc.) used to explore matter, biology, chemistry, and physics at atomic scales.

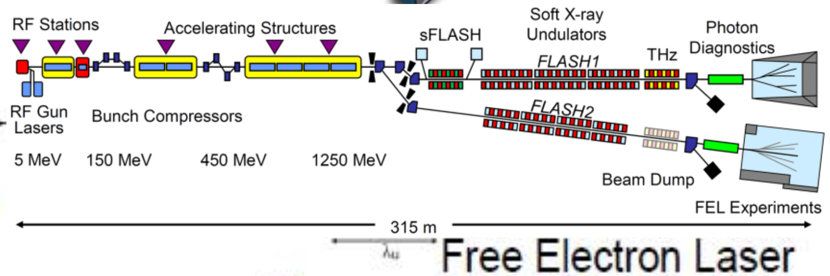
- Accelerator
  - accelerate charged particle



- Light source
  - accelerator-based

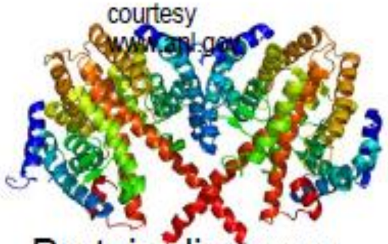


Synchrotron Radiation

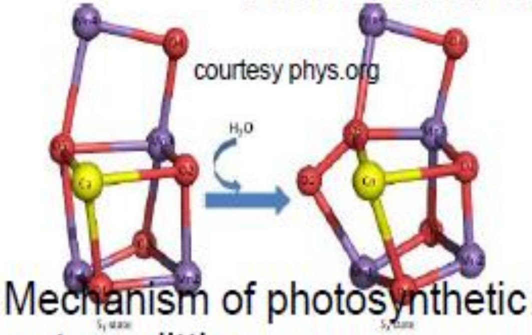


Free Electron Laser

- Applications



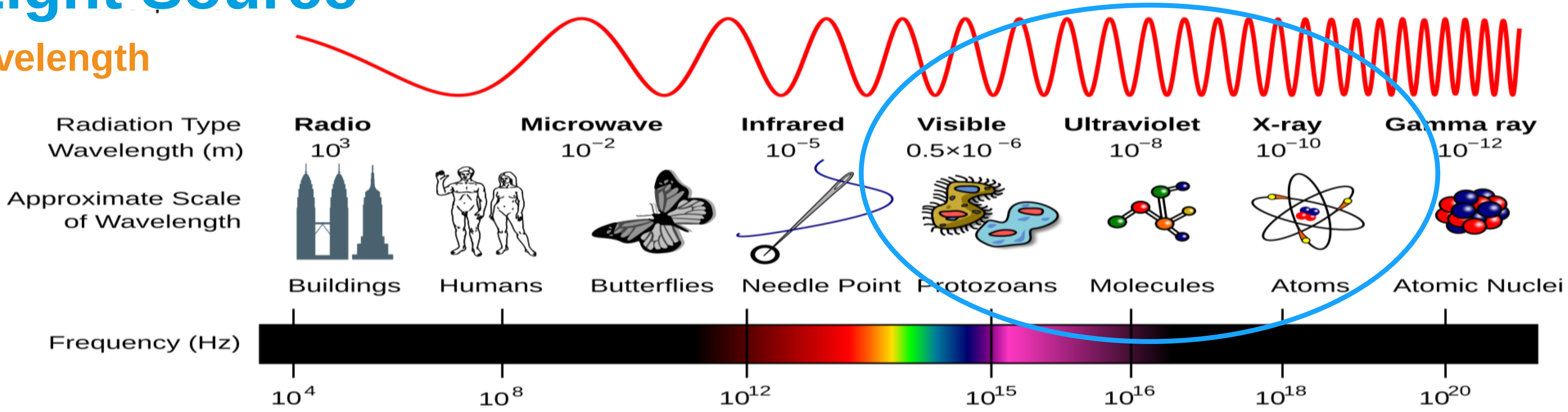
Protein discovery at ANL



Mechanism of photosynthetic water-splitting

An ideal Light Source

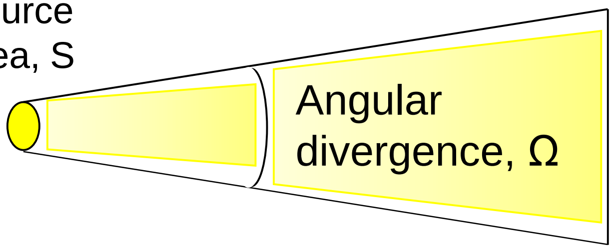
1. Tunable in wavelength



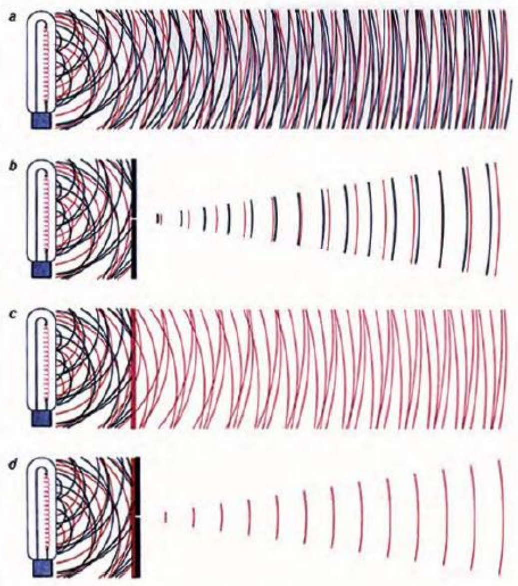
https://en.wikipedia.org/wiki/Electromagnetic_spectrum

2. Highly Brilliant

$$Brightness = constant\ \frac{F}{S\ x\Omega}$$



3. Fully Coherent

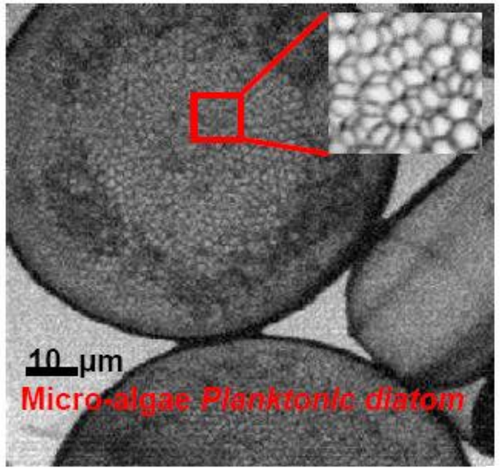


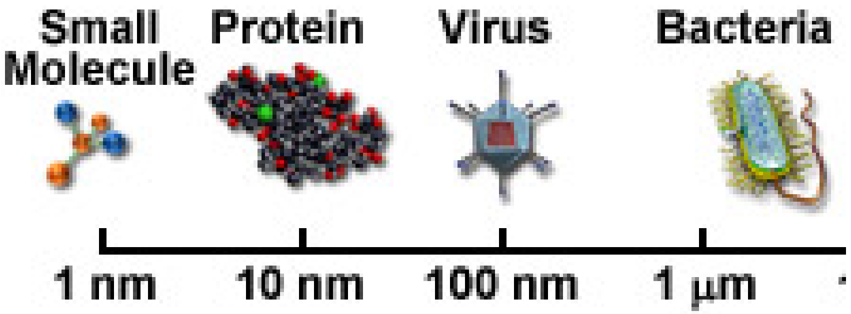
Courtesy of A. Schawlow, Stanford.

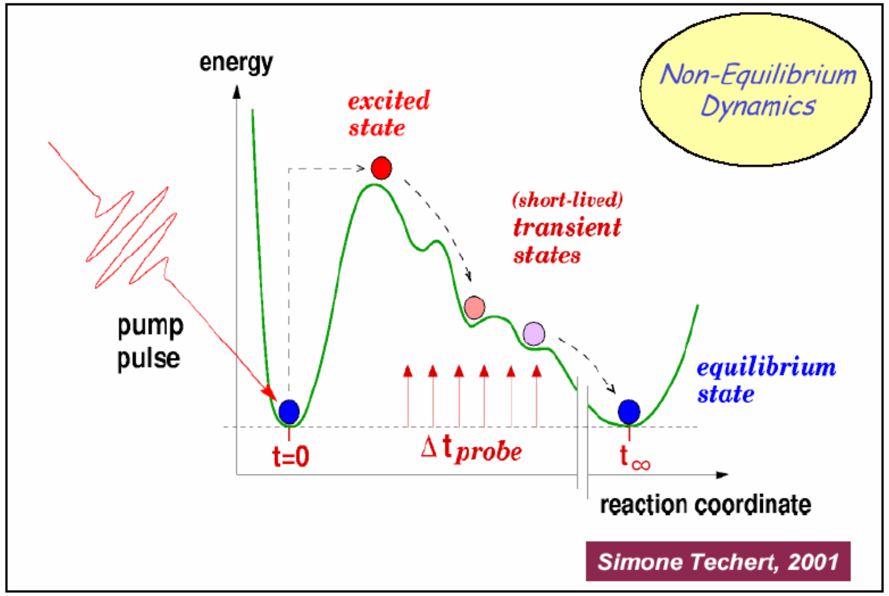
multi-color	X
wide source	X
multi-color	X
Collimated	√
Monochromatic	√
wide source	X
Monochromatic	√
Collimated	√
= coherent	

User's wishes

- High resolution at small spatial scales
  - ➢ ***Short wavelength***
- Large statistics in single-shot
  - ➢ ***narrow bandwidth***
- Stroboscopic picture of chemical processes
  - ➢ ***Short pulse***
- Large statistics in multi-shot
  - ➢ ***large number of photons per pulse (Peak intensity)***
- Most of the photons at the same wavelength
  - ➢ ***Large number of pulses per second (Repetition rate)***







Light Sources

Generation	Purpose	Radiation	Brilliance	Bandwidth / Coherence
1st (1960s)	Nuclear Physics (parasitic use)	Broad, non-optimized	Low	Broad bandwidth, incoherent
2nd	Dedicated light sources (bending magnets)	Broad, better-controlled	Medium	Still incoherent, broad
3rd (1990s)	Optimized with undulators	Narrower, tunable, directional	High	Quasi-monochromatic, partial coherence
4th	Free-Electron Lasers (FELs)	Laser-like, coherent radiation	Extremely high(Peak)	Narrow bandwidth, full spatial & temporal coherence

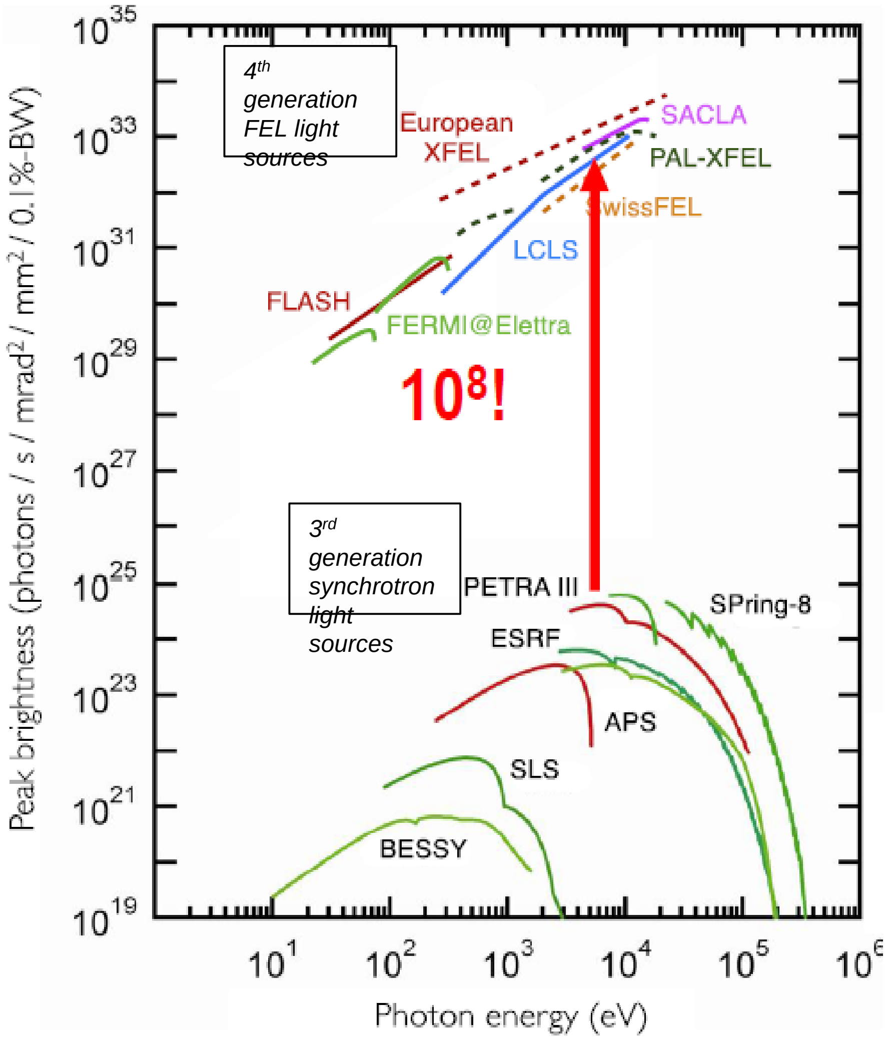
Free-electron Lasers

Core Features

- **Tunability:** FELs offer tunable output across a broad range of wavelengths, from the infrared to X-rays. Wavelength tunable down to 1A → atomic scale resolution

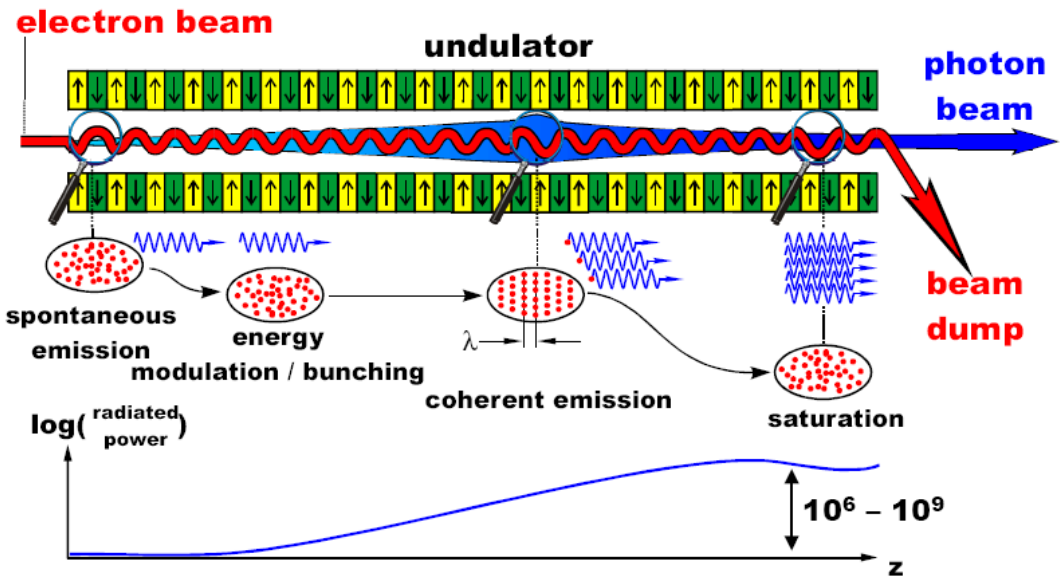
One of the primary advantages of FELs is that, in contrast to conventional lasers, the radiation wavelength can be varied by simply changing the electron energy

- **Ultrashort Pulses:** (fs scale) → molecular movies
- **Coherence:** FELs exhibit high temporal and spatial coherence → Monochromatic √ Collimated √ → single nanoscale objects
- **High Brightness:** This high brightness is beneficial for applications requiring intense and focused beams, such as materials science, biology, and imaging.
- Modern FELs such as FLASH, the European XFEL, and LCLS can reach peak magnitudes on the order of 10^{33}



FEL Requirements on e-beam

Pierce Parameter



- Radiation Power: $P(s) = P_0 e^{\frac{4\pi\sqrt{3}}{\lambda_u}\rho s}$
- Radiation Power at Saturation: $P_{sat} \sim \rho P_b$, $P_b = E_b$I/e
- FEL Power Saturation Length: $L_{sat} \sim \frac{\lambda_u}{\rho}$
- And pierce parameter depends on , Beam Energy, Peak Beam Current, Trans beam size → emittance and Undulator

e-beam Peak Current

Undulator Parameter

$$\rho = \frac{1}{4}[\frac{1}{2\pi^2}\frac{I_{PK}}{I_A}\frac{\lambda_u}{\beta\varepsilon_N}(\frac{K}{\gamma})^2]^{\frac{1}{3}}$$

Trans Emittance

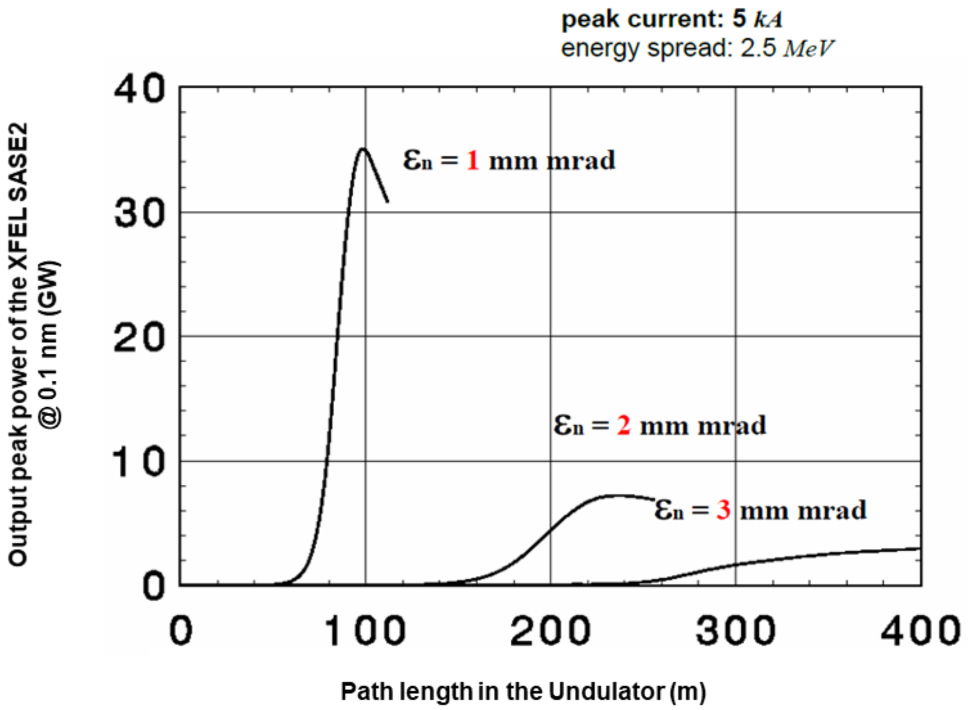
e-beam energy

- To have a large ρ (for a given lasing wavelength), we need a beam at the undulator with **high peak current**, **small transverse emittance**, **small energy spread**

SASE FEL Requirement on e beam

- Basic scaling laws for a Self-Amplified Spontaneous Emission FEL that drive the layout of facility:
- $\varepsilon_N < \gamma \frac{\lambda_r}{4\pi}, \varepsilon_N$: Normlized emittance, λ_r *the FEL resonant wavelength and* γ *the relativistic factor*
- The resonant condition is written as $\lambda_r = \frac{\lambda_u(1+K^2)}{2\gamma^2}$, K = 93.4 $\lambda_u B_{RMS}$ is undulator period, B_{RMS} is the RMS undulator field, λ_u is the undulator period length
- The gain length is : $L_g = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$
- The FEL Parameter:$\rho = \frac{1}{4}[\frac{1}{2\pi^2}\frac{I_{PK}}{I_A}\frac{\lambda_u}{\beta\varepsilon_N}(\frac{K}{\gamma})^2]^{\frac{1}{3}}$,
- I_{PK} is the peak current, $I_A \approx$ 17kA ,
- Energy spread has to be smaller $\frac{\sigma_E}{E} < \rho$

Transverse Emittance of e beam cannot be improved in a LINAC →has to be minimized at the Injector



W. Decking, Proceedings of the 27th International Free Electron Laser Conference

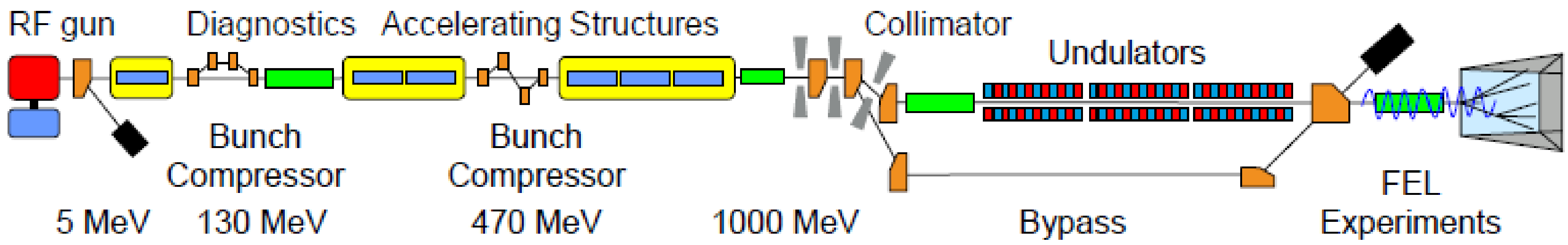
XFEL key component: → high brightness electron source

Why electron injector is so important?

→ property of linacs: beam quality will DEGRATE during acceleration in linac

→ electron source has to produce lowest possible emittance !!

Example soft x-ray SASE-FEL: original FLASH design



- High phase-space density:
  - short bunch length
  - small energy spread
  - high bunch charge
  - small area in the phase space (Emittance)

- Low emittance is a key figure of merit for circular and linear colliders and FELs
- High photon brightness → low electron beam emittance

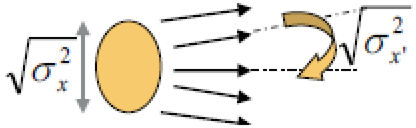
Emittance

A measure of beam quality

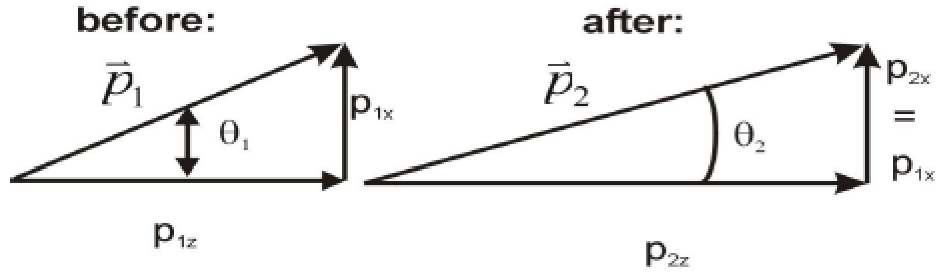
ε = 6 dimensional phase space volume occupied by given number of particles

long.: ε_z ~ (e^- bunch length) • (energy spread of e^- bunch)

trans.: $\varepsilon_{x,y}$ ~ (e^- beam size) • (e^- beam angular divergence)

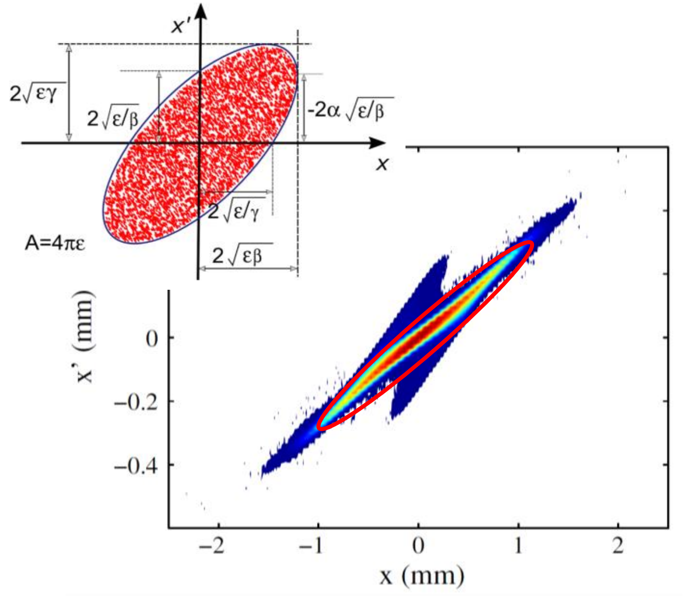


effect of acceleration on transverse emittance (adiabatic damping):



$\theta_2 < \theta_1$

$\Rightarrow$ angular divergence is reduced $\Rightarrow$ $\beta \bullet \gamma \bullet \sqrt{\sigma_{x'}^2}$



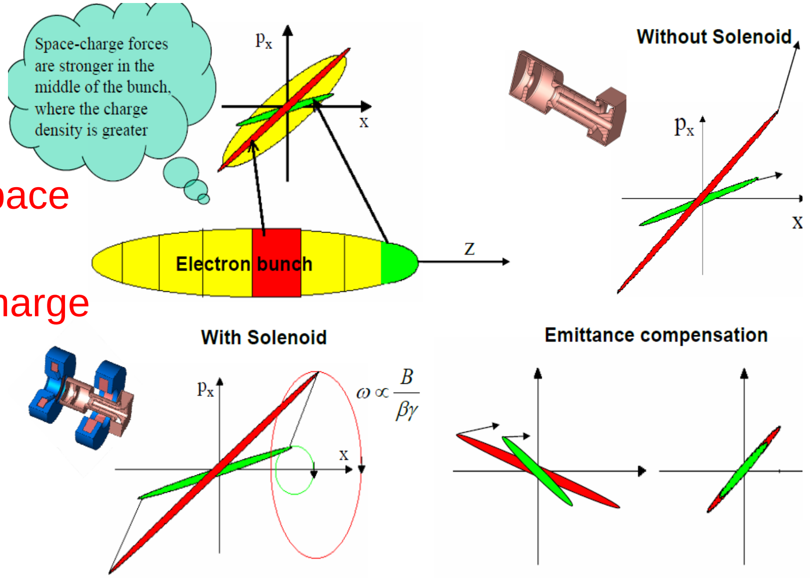
$\Rightarrow$ normalized RMS transverse emittance:

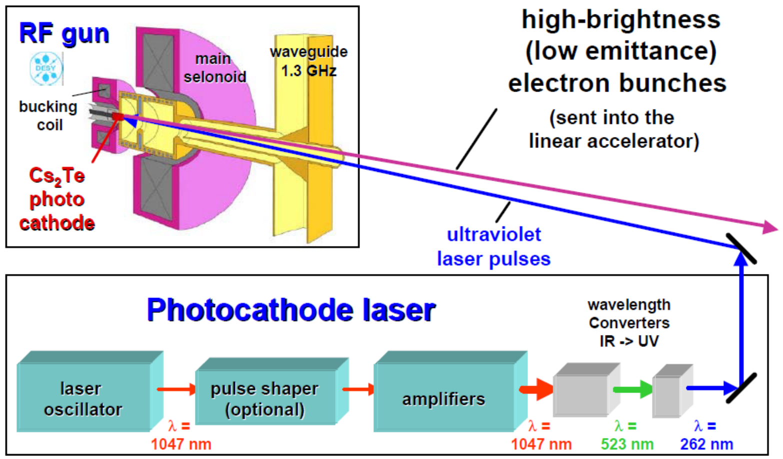
$$\varepsilon_x^n = \beta \bullet \gamma \bullet \sqrt{\sigma_x^2 \bullet \sigma_{x'}^2 - \mathrm{cov}^2(x, x')}\ ; \quad \beta = \frac{v}{c}, \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}, \quad x' = \frac{dx}{ds}$$

(ε^n is conserved in general)

Beam Quality determination at Source

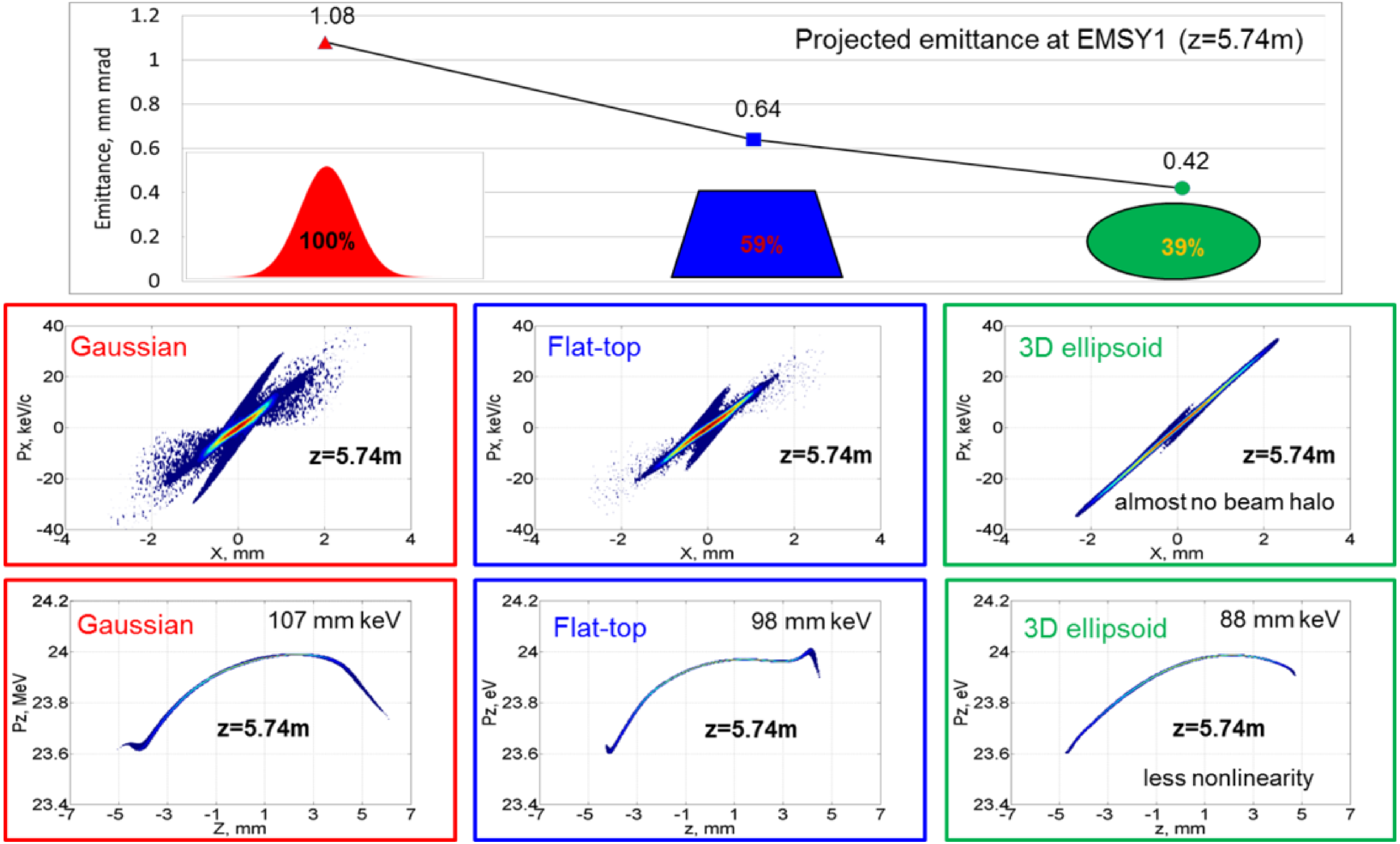
- Performance of machine depends on the quality of the beam generated by the injector the RF Gun
- The emittance growth in the RF gun occurs close to the cathode surface due to the **defocusing space-charge forces**, → where the beam is non relativistic.
- The minimization of defocusing space-charge forces is required to obtain the min emittance which is basic requirements for FELs
- It can be done by
  - Gun Gradient is important to reduce the emittance, increased gradient reduces space charge forces
  - Cathode properties to have less space charge (Green Cathodes)
  - Photo Injector Laser (PIL) temporal and transverse profile
  - Magnetic focusing of RF gun





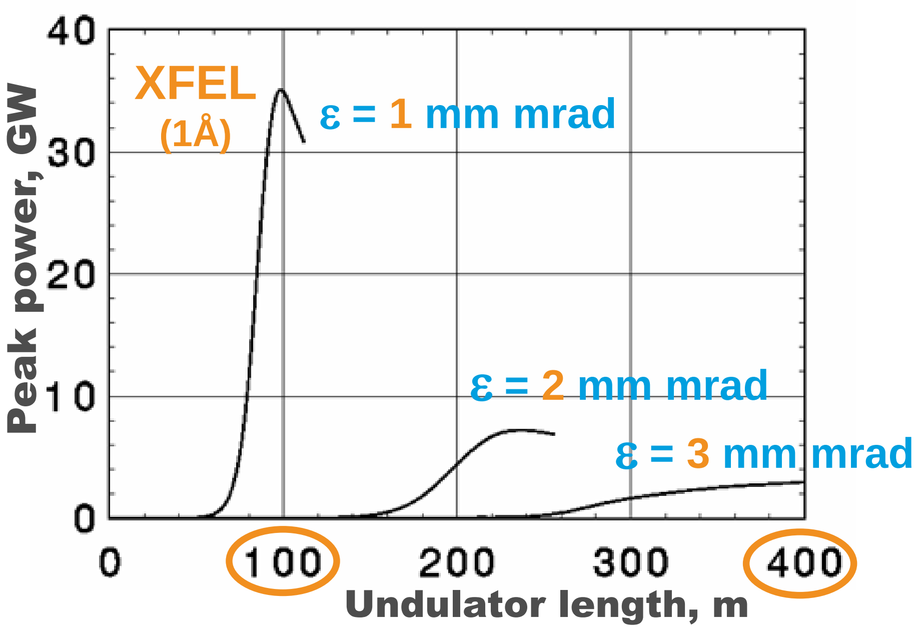
K. Floettmann, DESY Hamburg

Laser shaping

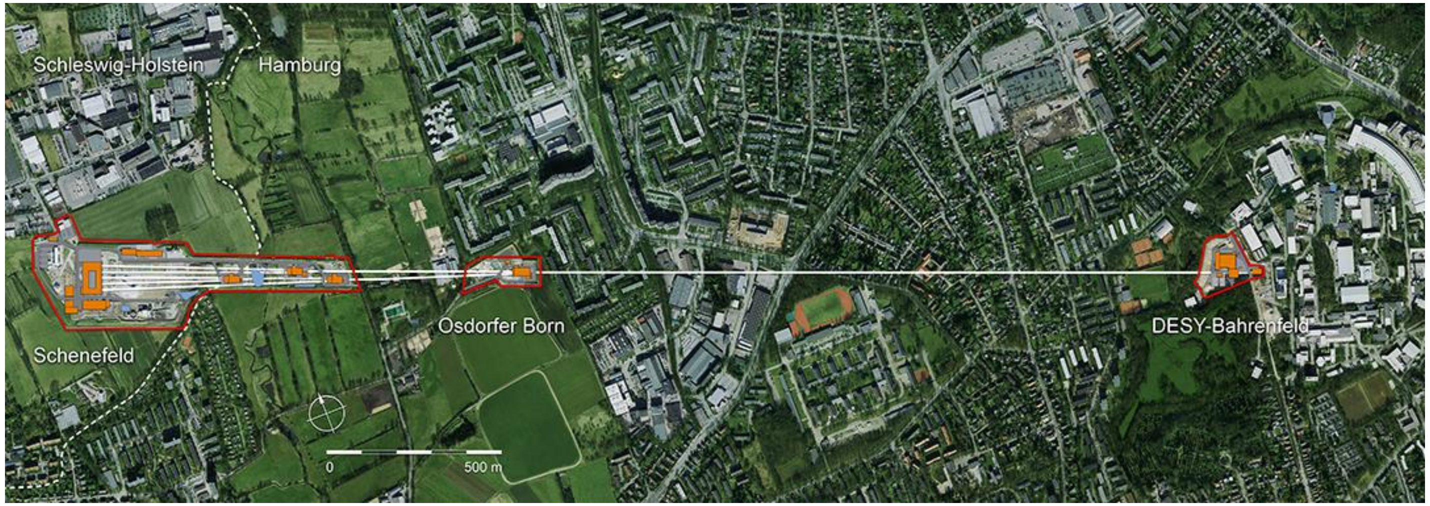


High density of the electron beam phase space

Why electron beam emittance must be small



The European X-Ray Free Electron Laser (EXFEL) in Hamburg, Germany



Beam emittance in linear accelerators can only increase ➔
➔ High Brightness Electron Source required to start with smallest possible emittance

E-beam brightness: $B \propto \frac{2I}{\varepsilon_x \varepsilon_y}$

Goal emittance for the XFEL:
0.9 mm mrad @ injector
1.4 mm mrad @ undulator entrance

PITZ

Scope

- Conditioning and characterizing gun
- R&D
  - Photoemission studies
  - Laser shaping
  - Diagnostics methodologies
- Applications
  - High Brightness Beams for FELs
  - TeraHertz Radiation
  - Radiation therapy

PITZ evolution 2002 - 2022

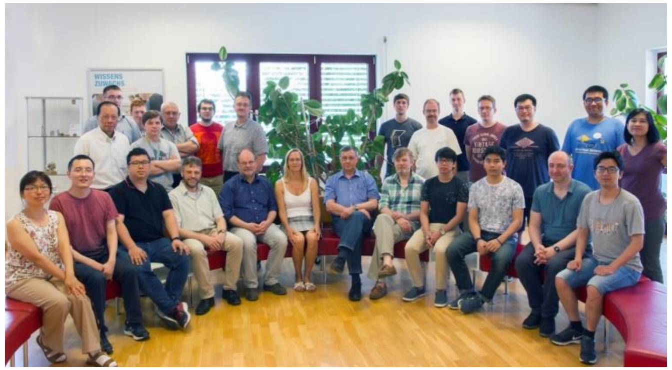
Primary goal: improve emittance

	Year-->	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2025
gun	cavity	Gun2	FLASH	Gun1		Gun3.1 FLASH	G3.2	Gun4.2	FLASH	Gun4.1		FLASH G3.1	FLASH 4.3 XFEL	G4.4 XFEL	Gun4.2	Gun4.6	XFEL	4.5	Gun4.2		Gun5.1		Gun5.2
gun	Ez,MV/m	35	37	42-->60		43				60													
gun	Ebeam	~4MeV		4.3MeV-->6MeV		4.5MeV								~6.5MeV									
boo	cavity	no			TESLA at 2.5m		TESLA at 3.1m			CDS at 3m				CDS at 2.6m									
boo	Ebeam				~13MeV					~25MeV			22MeV*										
laser	temp ps	10	6/24\6				6/24\6	2/22\2						2/22\2	11*		~						~ 20
emit	EMSY1	z=1.618m			z=4.3m		z=5.74m							z=5.277m									
emit	Ldrift	1.01m			2.334m		2.64m							3.133m									
emit	method	center BL	3xBLs		e-meter	11xBLs			continuous synchronized (detailed) scan						+slice with TDS								
emit	min $\varepsilon_{n,xy}$ mm mrad (charge)		3 (1nC)	1.5-1.7 (1nC)		1.37 (1nC)	1.26 (1nC)		0.9 (1nC)		0.7 (1nC)				0.8 (0.5nC)								
PITZ goals		small emittance (nominal EXFEL)										+reliability at full performance			+emittance (EXFEL startup)								
												+THz idea		+plasma				+THz project			+Rad.Biology		

PITZ Collaboration Partners (formal contract signed)

contract on **green** photocathodes

- **Founding partners of PITZ:**
  - DESY, HH & Z (leading institute)
  - HZB (BESSY) (A. Jankowiak): magnets, vacuum
  - MBI (S. Eisebitt): cathode laser
  - TU Darmstadt (TEMF, T. Weiland, H. DeGersem): simulations



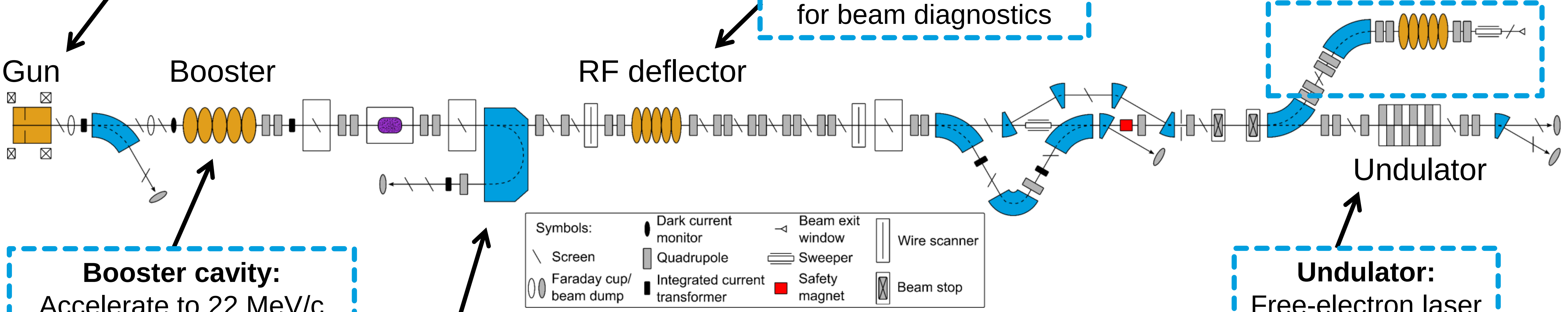
- **Other national partners:**
  - Hamburg university:
    - most PhD students;
    - HGF-Vernetzungsfond;
    - generation of short pulses
    - plasma experiments
  - HZDR:
    - BMBF-PC-laser-project between MBI, DESY and HZDR, until ~2009;
    - collaboration between HZB, HZDR, MBI and DESY in SC-gun-cluster
  - TH Wildau:
    - radiation biology and FLASH radiation therapy

- **International partners:**
  - IAP Nizhny Novgorod + JINR Dubna: 3D elliptical laser pulses, THz radiation (Currently suspended)
  - INFN Frascati + Uni Roma II (M. Ferrario, L. Palumbo): E-meter and TDS pre-studies
  - INFN Milano (C. Pagani): photocathodes
  - INR Troitsk (L. Kravchuk): CDS, TDS, Gun5 (Currently suspended)
  - INRNE Sofia (D. Tonev): EMSY + personnel
  - IJCLab Orsay (W. Kaabi): HEDA1 + HEDA2
  - UKRI Daresbury (D. Angal-Kalinin, B. Militsyn): phase space tomography
  - Thailand Center of Excellence in Physics (Duangmanee Wongratanaphisan, Ch. Thongbai): personnel
  - AANL (YERPHI) (G. Karyan) + CANDLE (B. Grigoryan), Yerevan: personnel
  - LBNL Berkeley (Th. Schenkel): PWFA, NC CW Gun
  - SLAC (N. Holtkamp): LCLS-I undulators

Photoinjector Test Facility at DESY in Zeuthen (PITZ)

Photoelectron gun:
Accelerate to ~7MeV/c

Transversely deflecting structure:
Transverse acceleration for beam diagnostics



Booster cavity:
Accelerate to 22 MeV/c

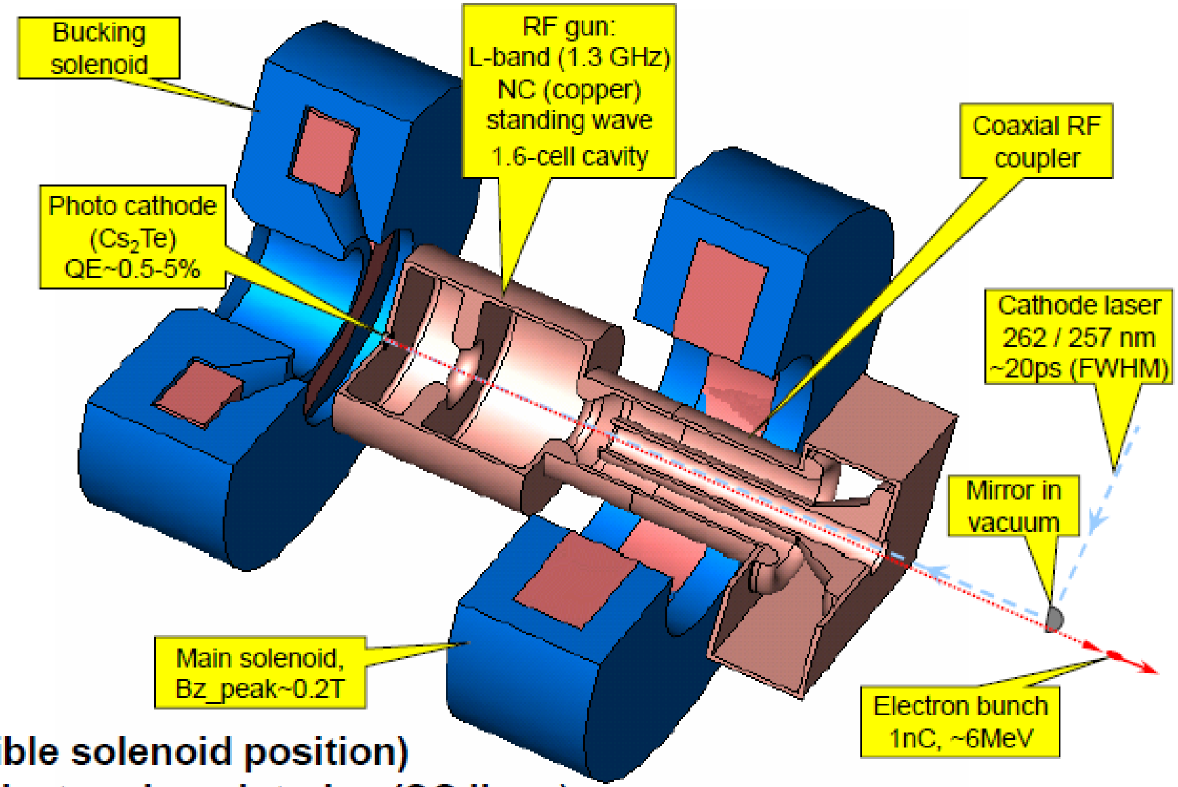
Dipole magnet:
Deflects beam
energy-measurement

Undulator:
Free-electron laser in THz (sub-mm) region

Solution to low emittance

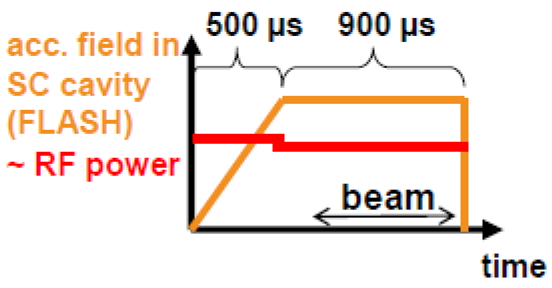
Photocathode RF Gun

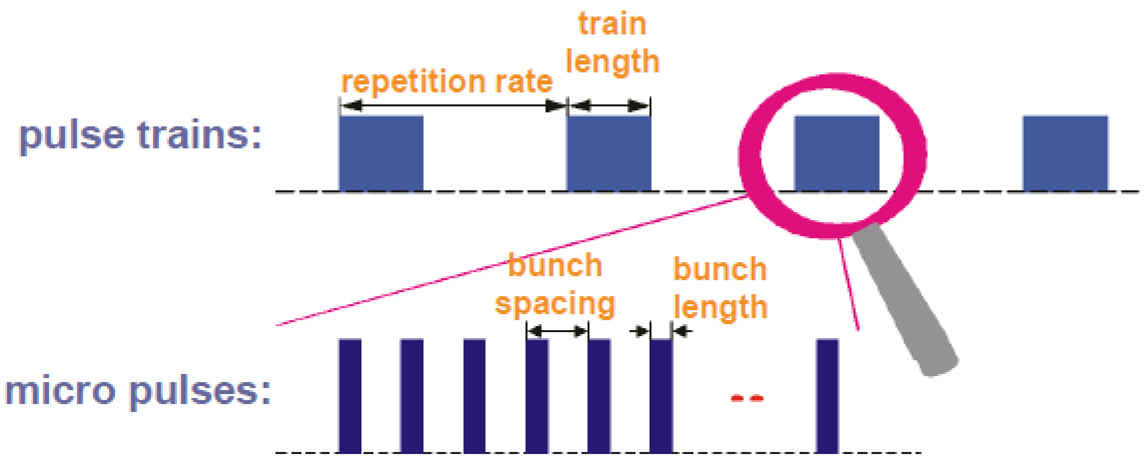
Example: PITZ gun



Main properties of PITZ gun:
1.3 GHz cavity, coaxial RF coupler (flexible solenoid position)
Capable of high average power → long electron bunch trains (SC linac)
Very low normalized transverse emittance

Some parameters of FLASH and Eu-XFEL

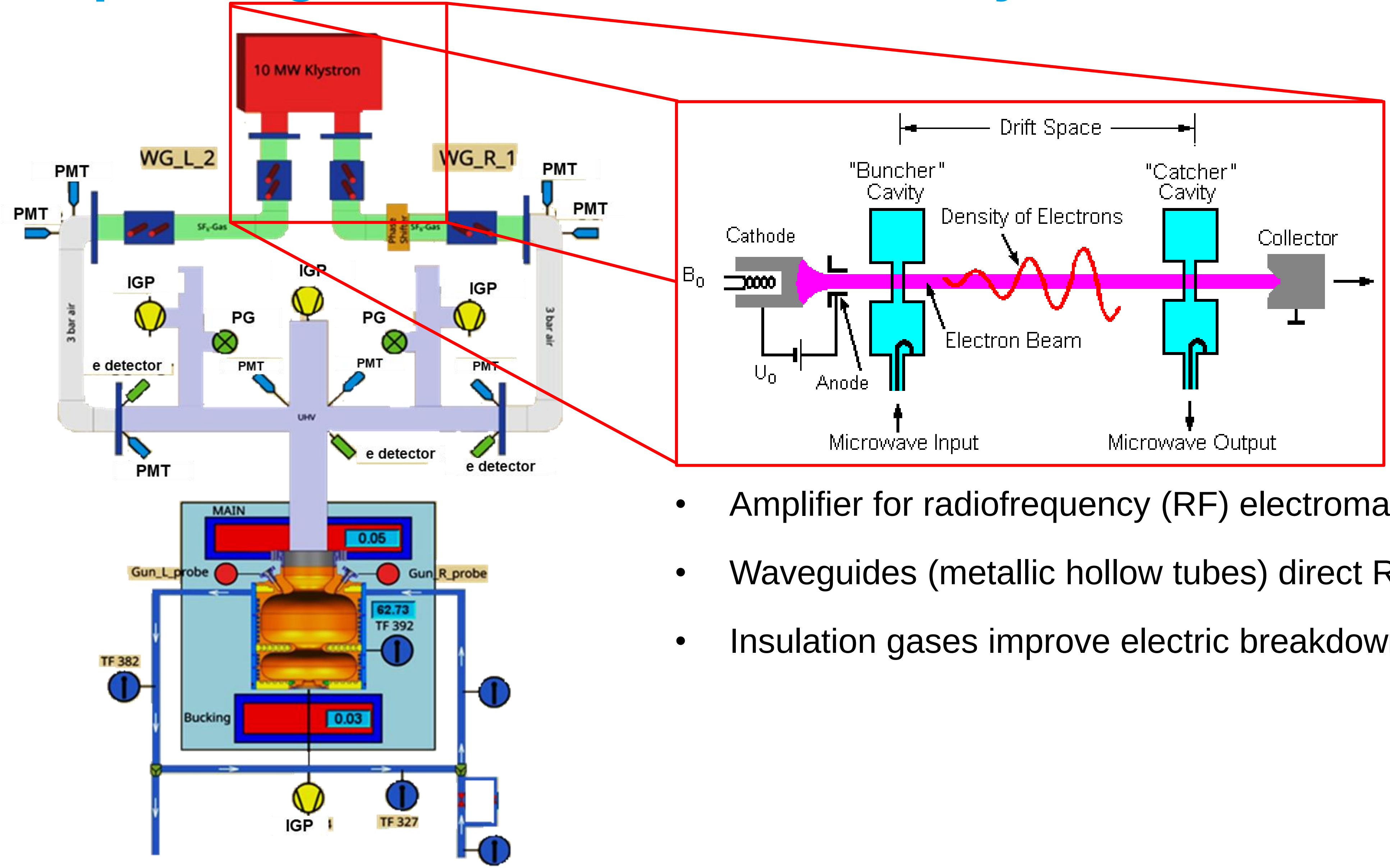




Parameters	FLASH	European XFEL
final beam energy	1.2 GeV	17.5 GeV
max. repetition rate	10 Hz	10 Hz
max. train length	800 µs	650 µs
bunch spacing	1 – 20 µs	0.2 – 1 µs
required injector emittance (1 nC)	2 mm mrad	0.9 mm mrad
SASE output wavelength	4 – 90 nm	0.05 – 4.7 nm

→ Gun 5 aims for 1ms !

Operating an acceleration RF cavity



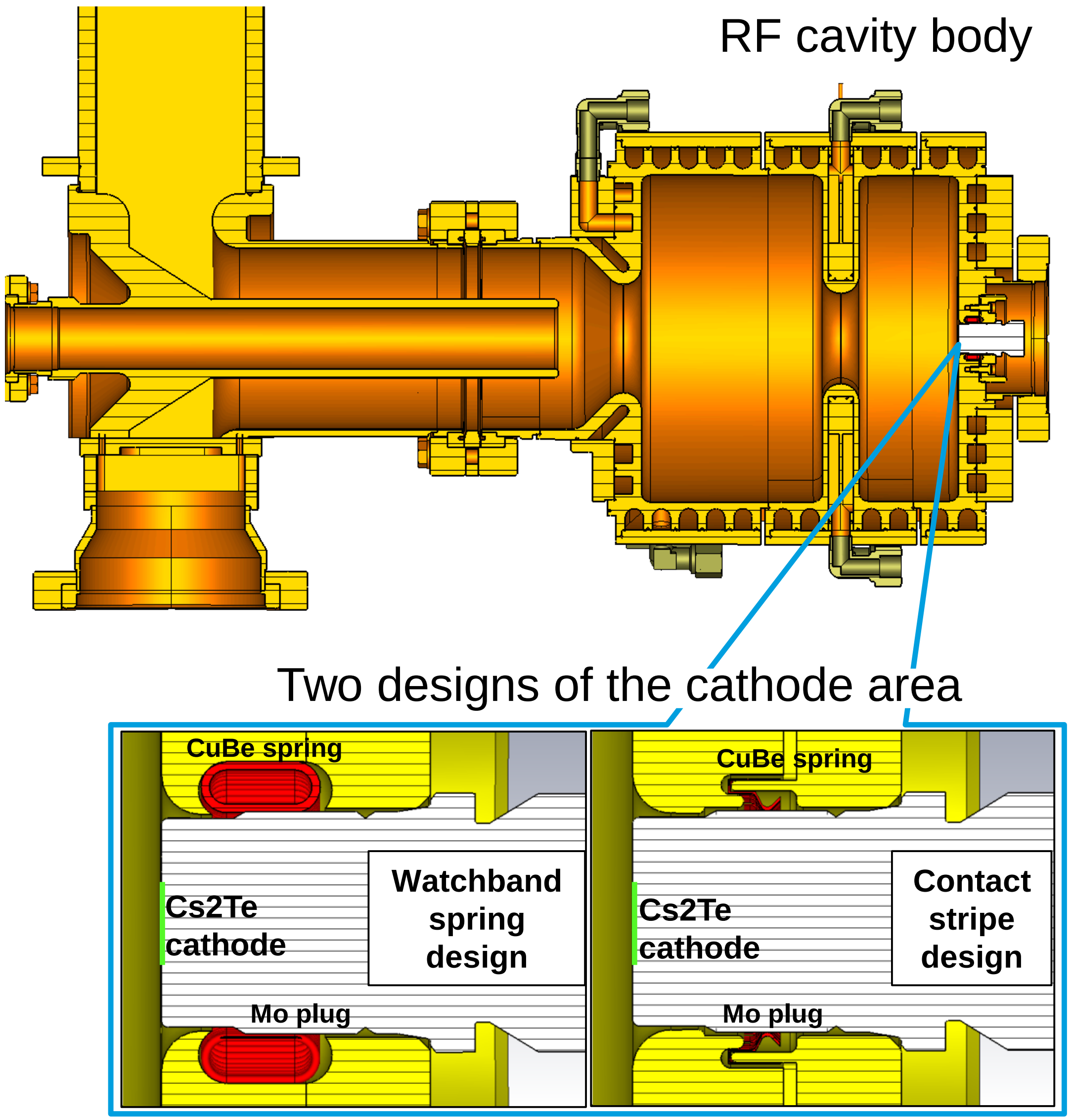
- Amplifier for radiofrequency (RF) electromagnetic wave
- Waveguides (metallic hollow tubes) direct RF to cavity
- Insulation gases improve electric breakdown threshold

RF cavity

The rf photoelectron gun cavity operates with a standing wave regime with a resonant frequency of 1.3 GHz

Main parameters

Parameter	Value
Max. accelerating gradient at the cathode, MV/m	**60**
Frequency, MHz	**1300**
Unloaded quality factor	~20000
Beam momentum after gun, MeV/c	7
RF peak power, MW	**6.5**
RF pulse duration, µs	**≤650**
Repetition rate, Hz	10

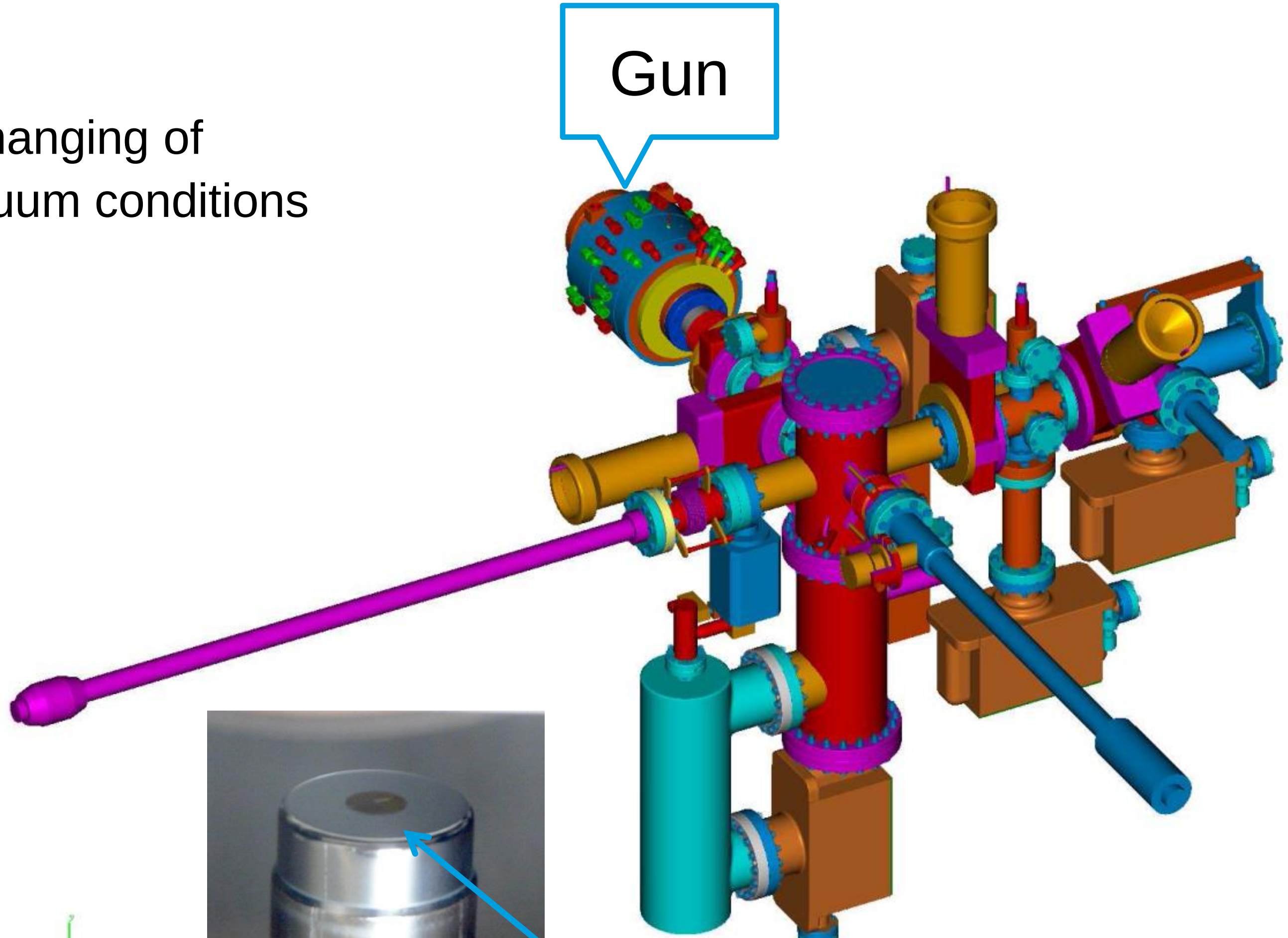


Photocathode load-lock system

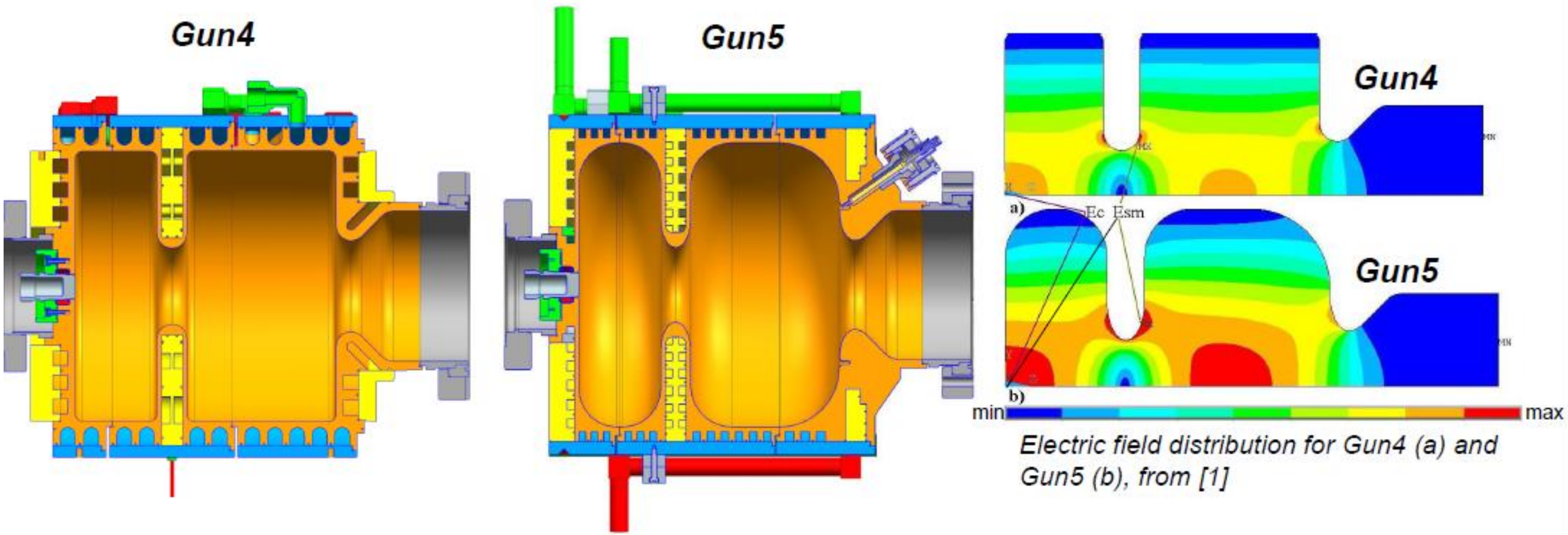
A load-lock cathode system allows mounting and changing of cathodes while maintaining excellent ultra-high vacuum conditions

Cathode plug

CsTe surface for photoemission



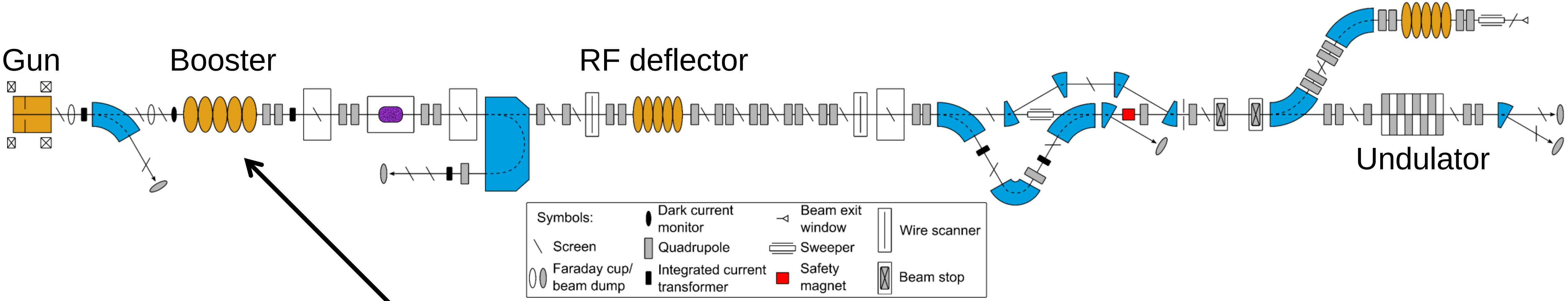
Gun designs



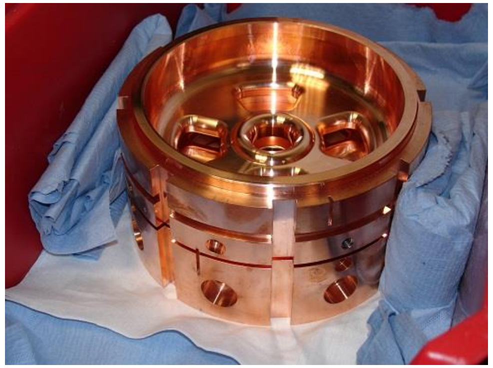
Electric field distribution for Gun4 (a) and Gun5 (b), from [1]

- **Optimised cell shape** for higher RF **efficiency** and reduced peak **surface field** for same cathode gradient
- Direct field measurements inside the Gun with the help of a **RF probe**
- Higher **cooling efficiency** (Gun 5: 61.3 kW average RF power, 6.13 MW for **1 ms @ 10 Hz**; from [2])

Overview of the PITZ beam line



Accelerating structures



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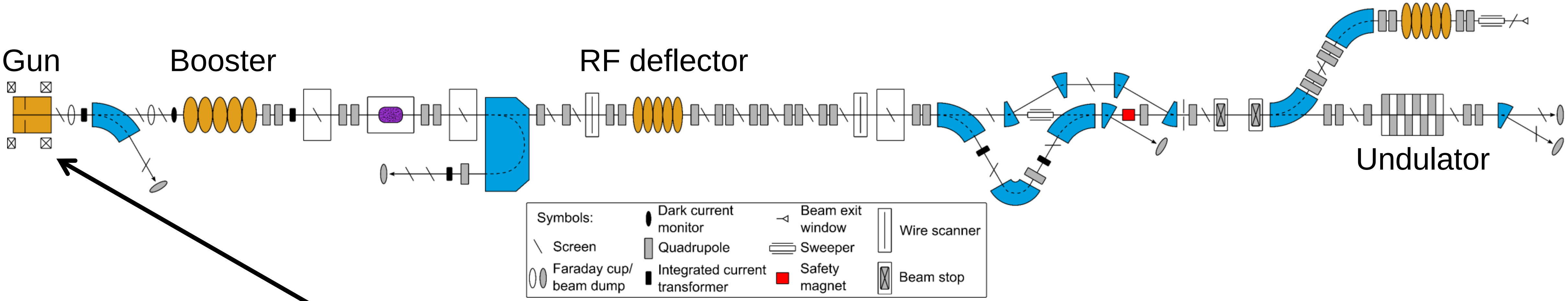
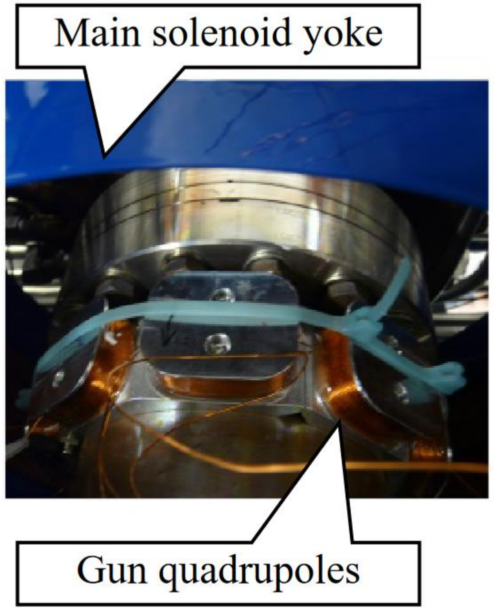


Solenoid magnets (focusing)



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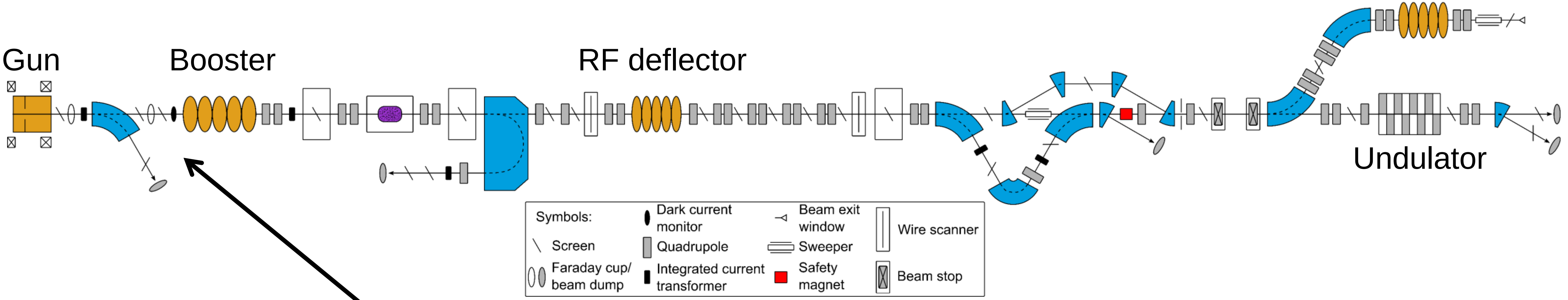
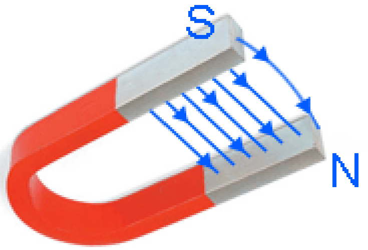
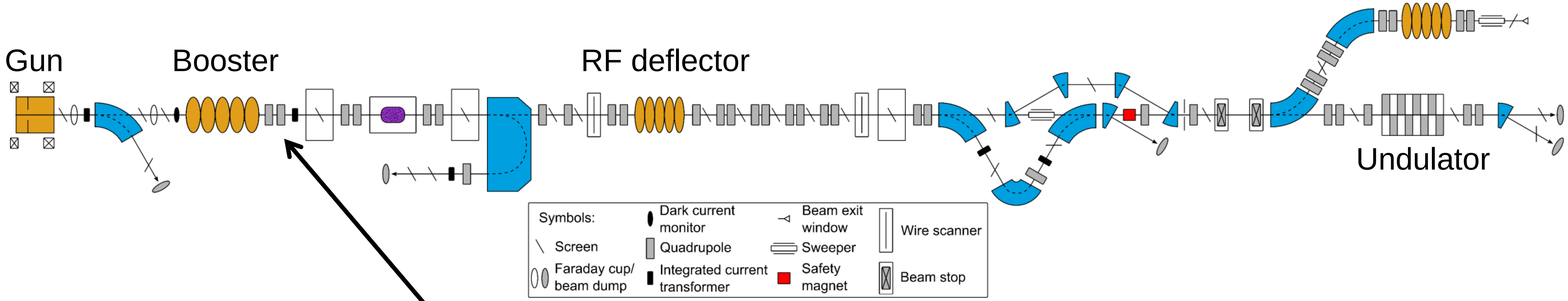


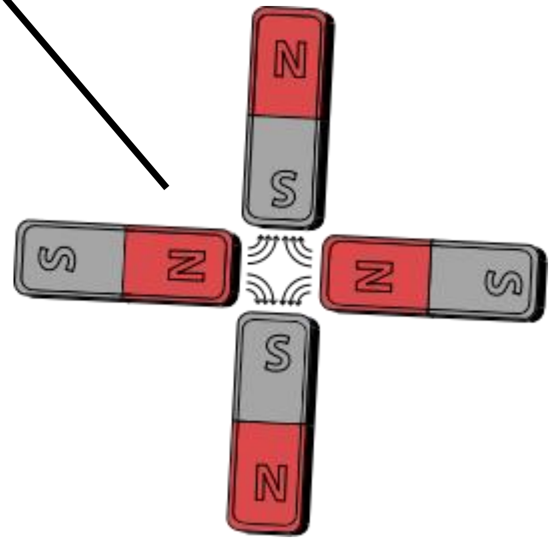
Steerer/corrector magnets
(distributed all over beamline)

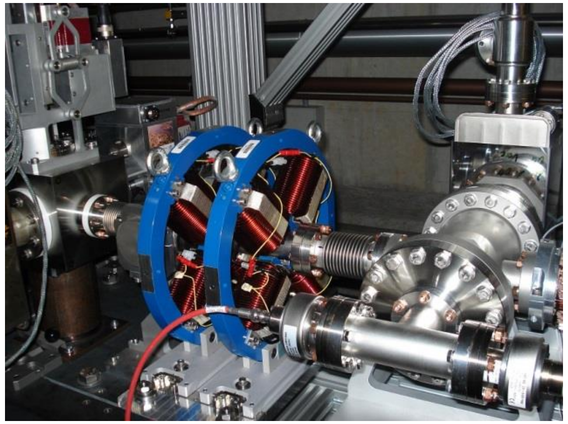


Overview of the PITZ beam line

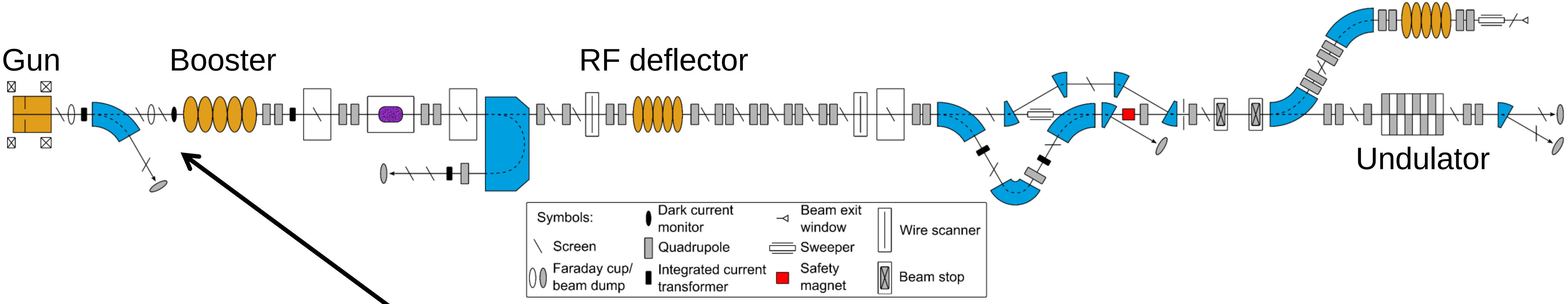


Quadrupole magnets



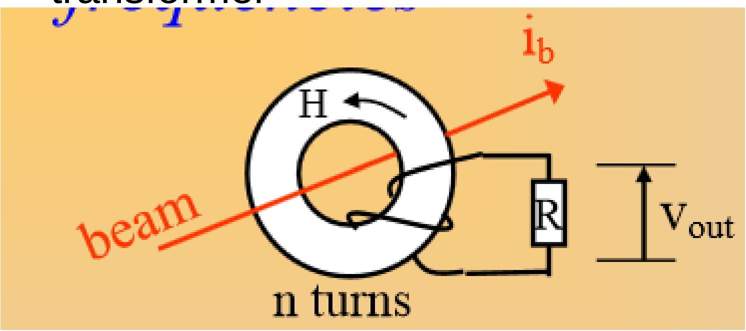


Overview of the PITZ beam line

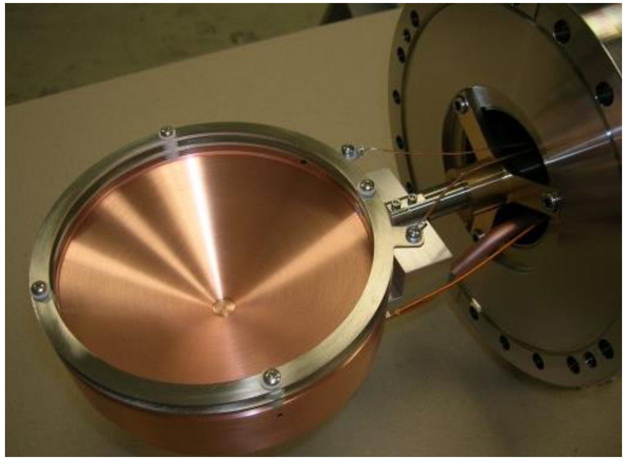


Charge measurement:
Faraday cups (FC)
Integrated current transformer

Current transformer

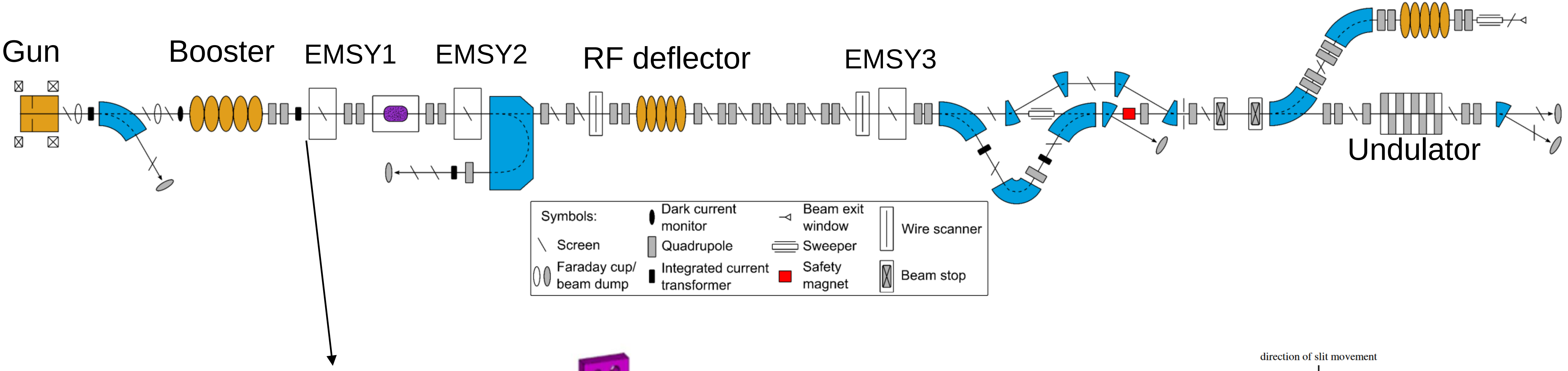


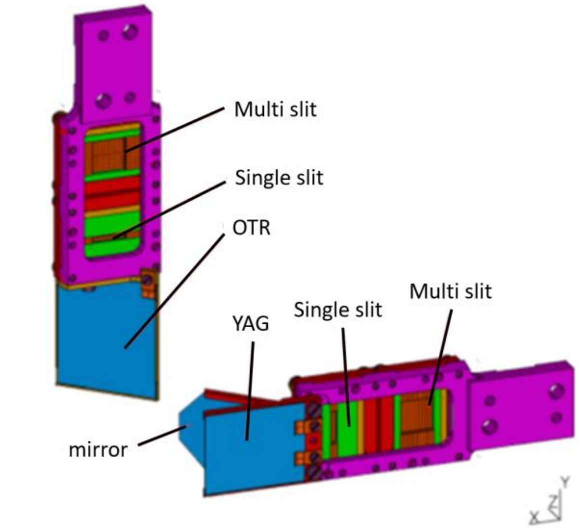
Faraday cup

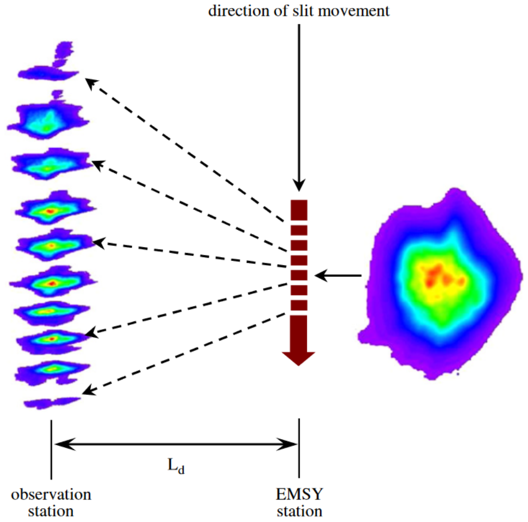


Overview of the PITZ beam line

Emittance Measurement SYstem (EMSY)

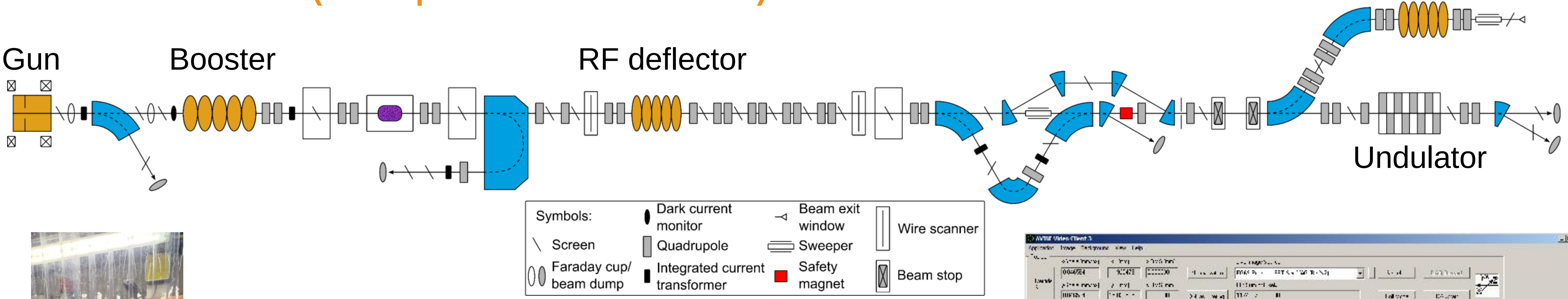


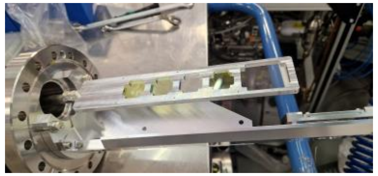


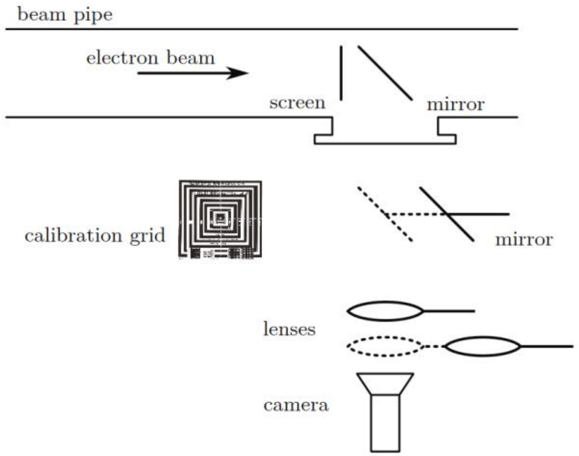


Overview of the PITZ beam line

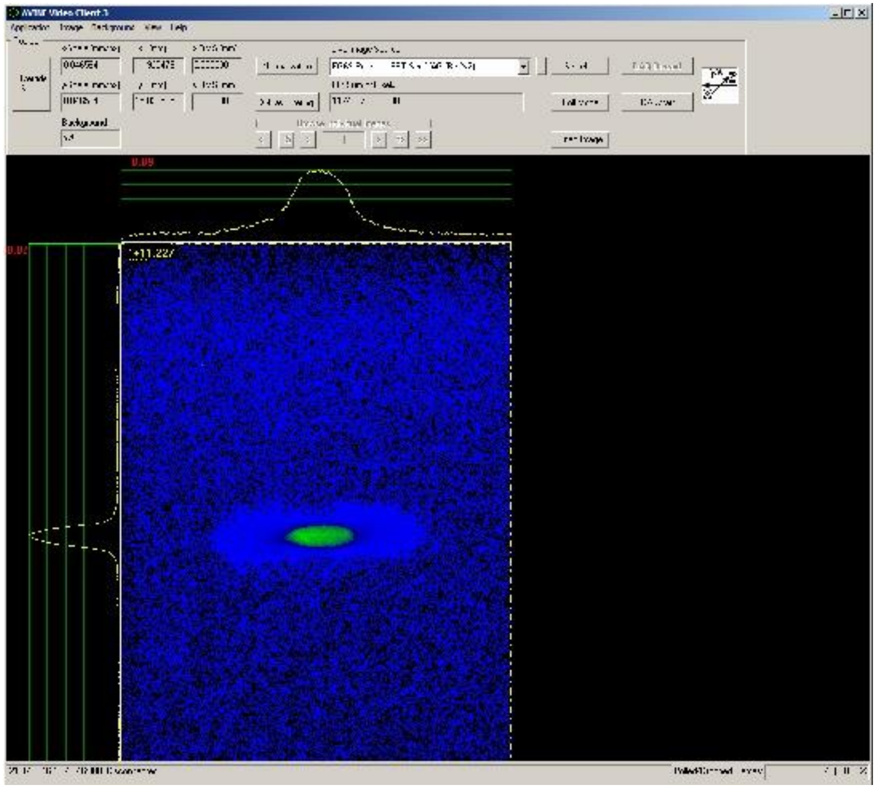
Scintillator screens (Beam position and beam size)



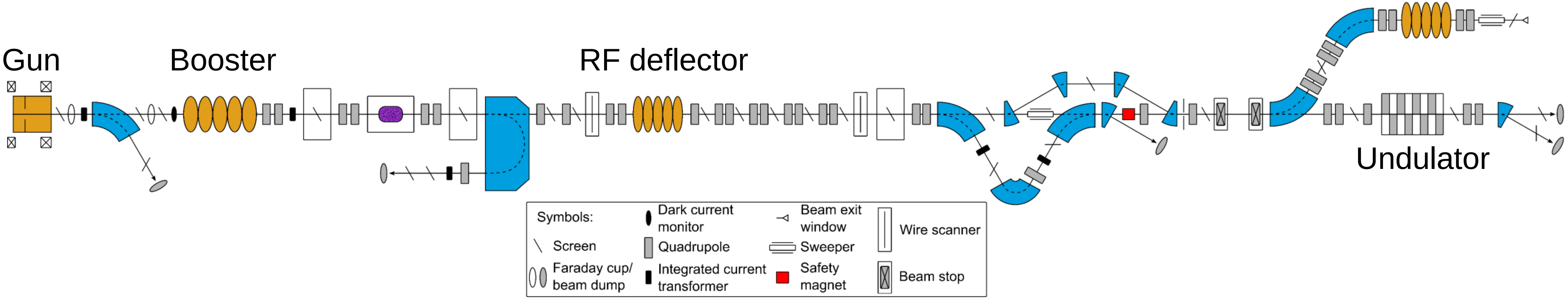




Beam on YAG screen



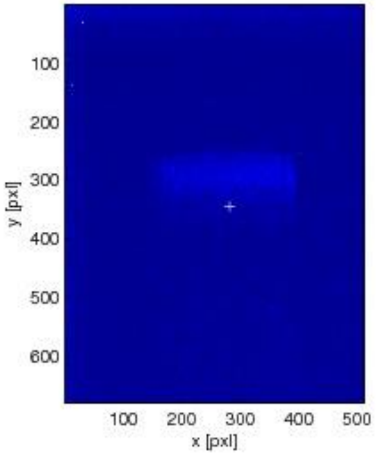
Overview of the PITZ beam line



Momentum distribution
(dispersive section)

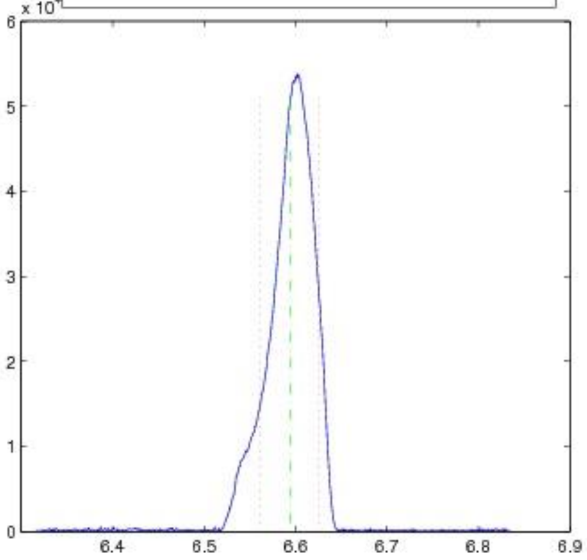
Phase: –148°

Statistics (Img): 100
Statistics (Bkg): 50

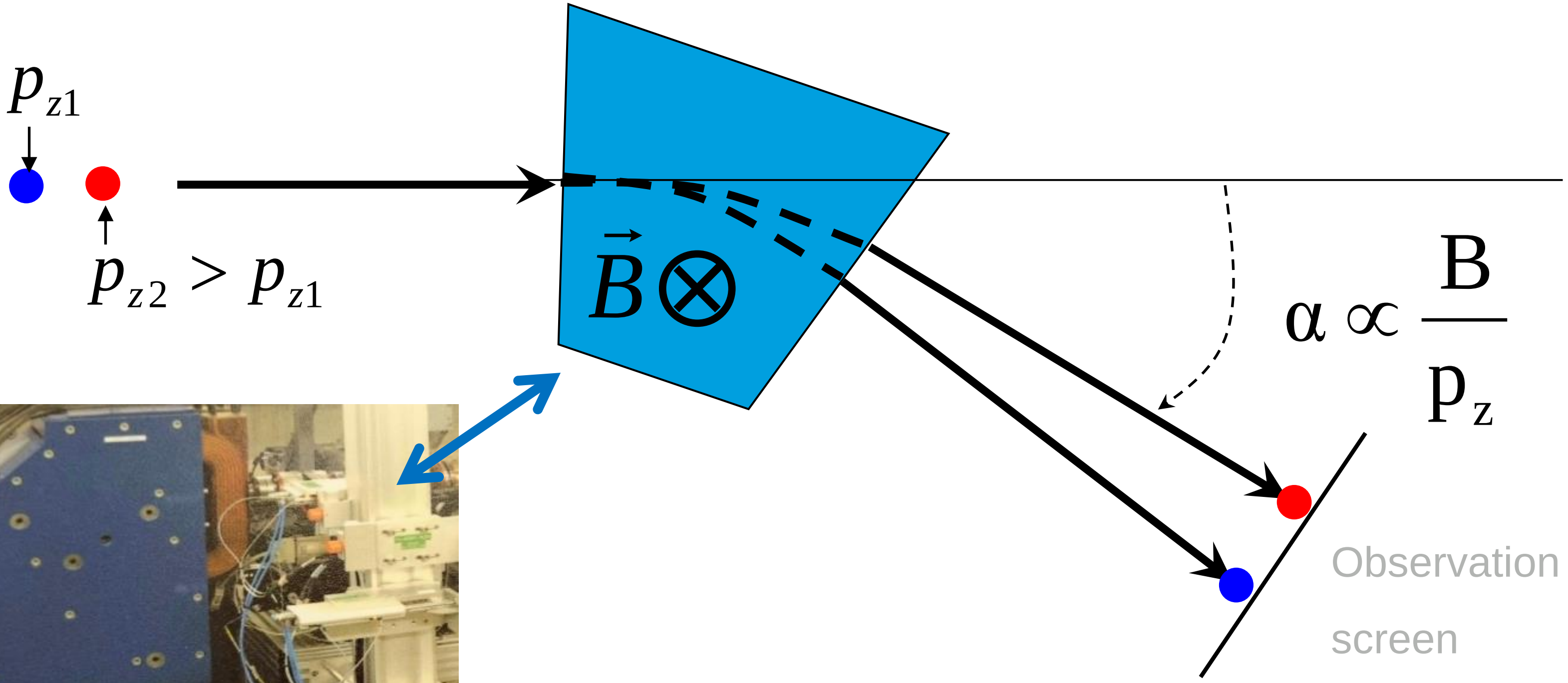


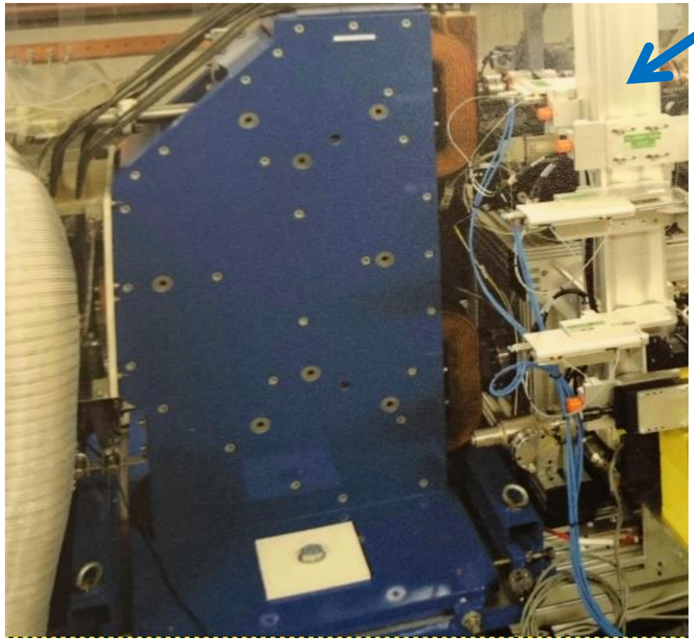
$\mathbf{p_{mean} = (6.594 \pm 0.003)MeV/c}$

$\mathbf{p_{RMS} = (32 \pm 6)keV/c}$



Measurements of momentum and momentum spread

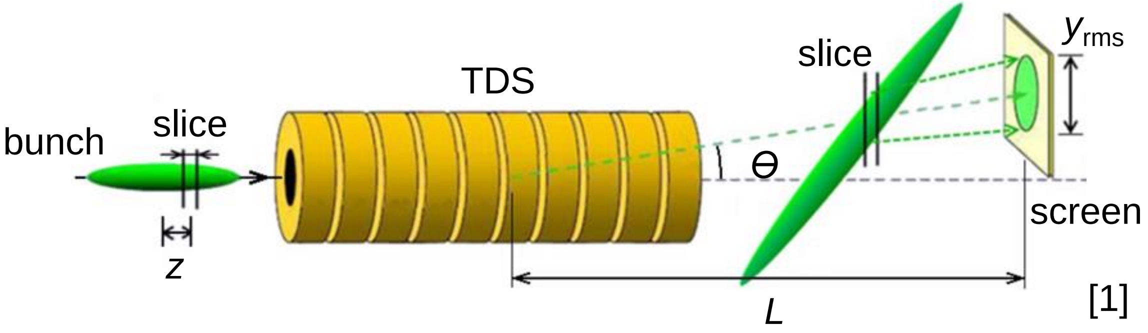




Transversely deflecting structure (TDS)

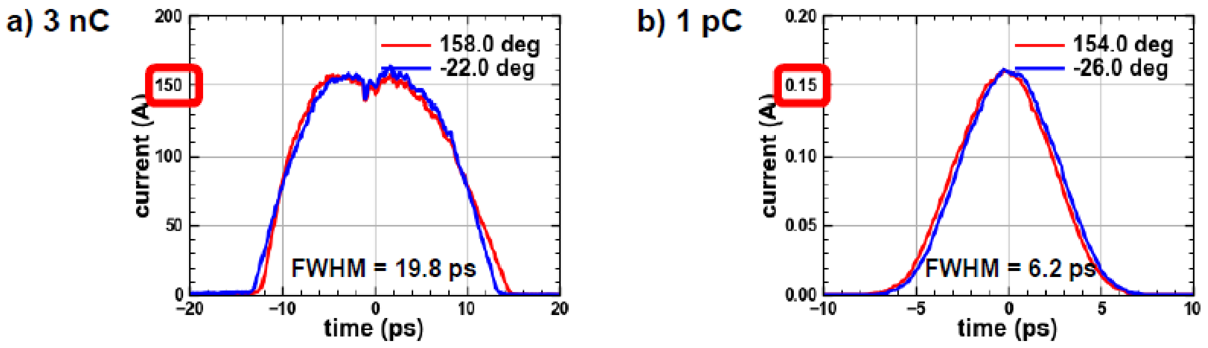
Mapping longitudinal to vertical coordinate

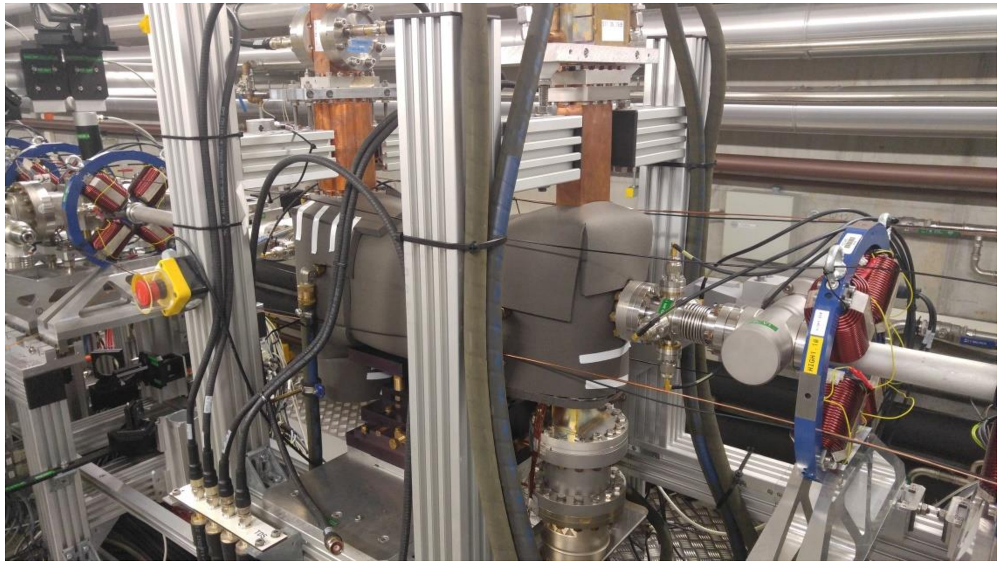
- Bunch profile
- Longitudinal phase space
- Time-resolved transverse phase space
  - **Slice emittance**



Properties

- European XFEL prototype
- 3 GHz (S band)





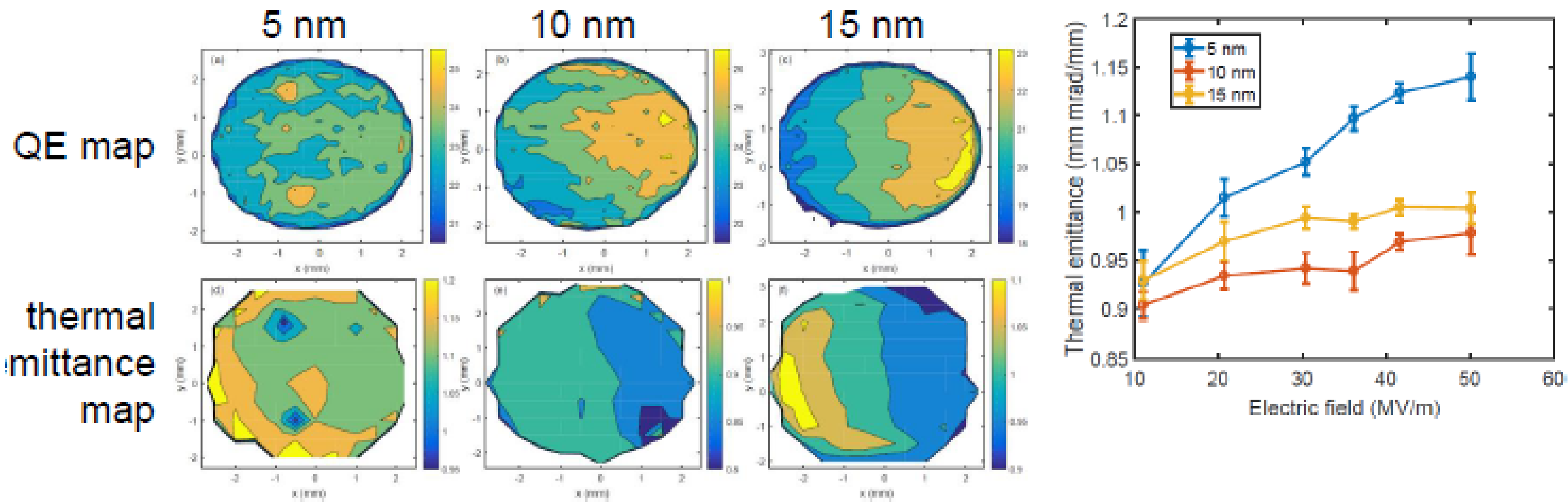
[1] D. Malyutin, Ph.D. thesis, Universität Hamburg, (2014)

Photocathode development

Up to now mainly UV cathodes (Cs2Te) were used at PITZ, INFN LASA Milano develops new green cathodes

Cs2Te:

- Developments for DESY machines for were done by **INFN LASA Milano**
- Standard production for DESY's facilities (XFEL, FLASH, PITZ) was taken over by DESY Hamburg, special cathodes are still developed by LASA
- Example: Cs2Te cathodes with different Te thicknesses:



▸ **Anti-correlation** between QE and thermal emittance observed

→ PRAB **25**, 053401 (2022)

Green cathodes:

- Emission at **green** PC laser **wavelength**
- Aim for
  - **Lower thermal emittance**
  - **Simplified photo cathode laser system** → omitting conversion to UV leads to
    - Lower primary laser energy required
    - **Less degradation of laser pulse shaping**
  - Low **dark current**, high **life time + robustness** to be maintained
- New developments at LASA ongoing …

Photoemission

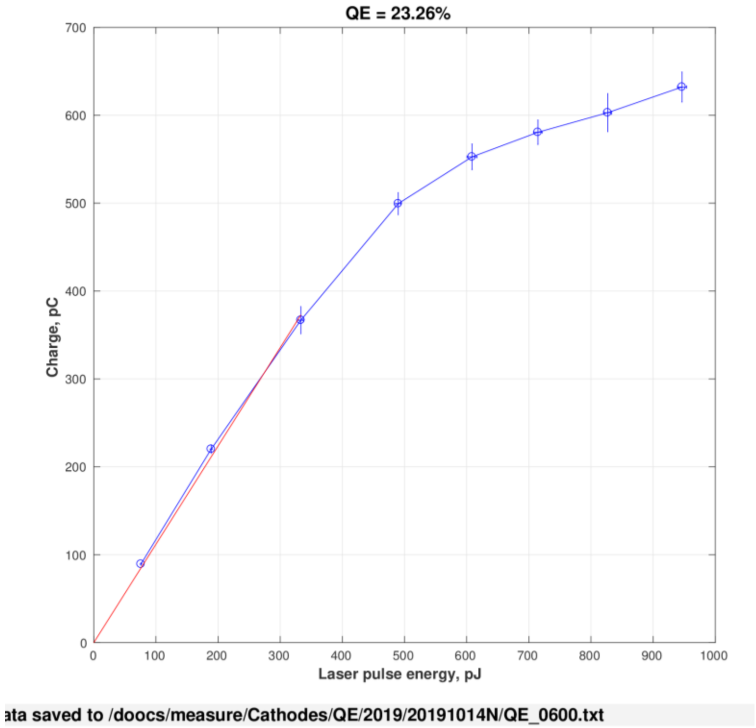
Quantum efficiency is defined as the number of electrons emitted divided by incident number of laser photons.

Electron bunch charge (in coulomb)

$$Q = \frac{W}{\hbar\omega} Q.E.$$

where W = laser pulse energy (J)

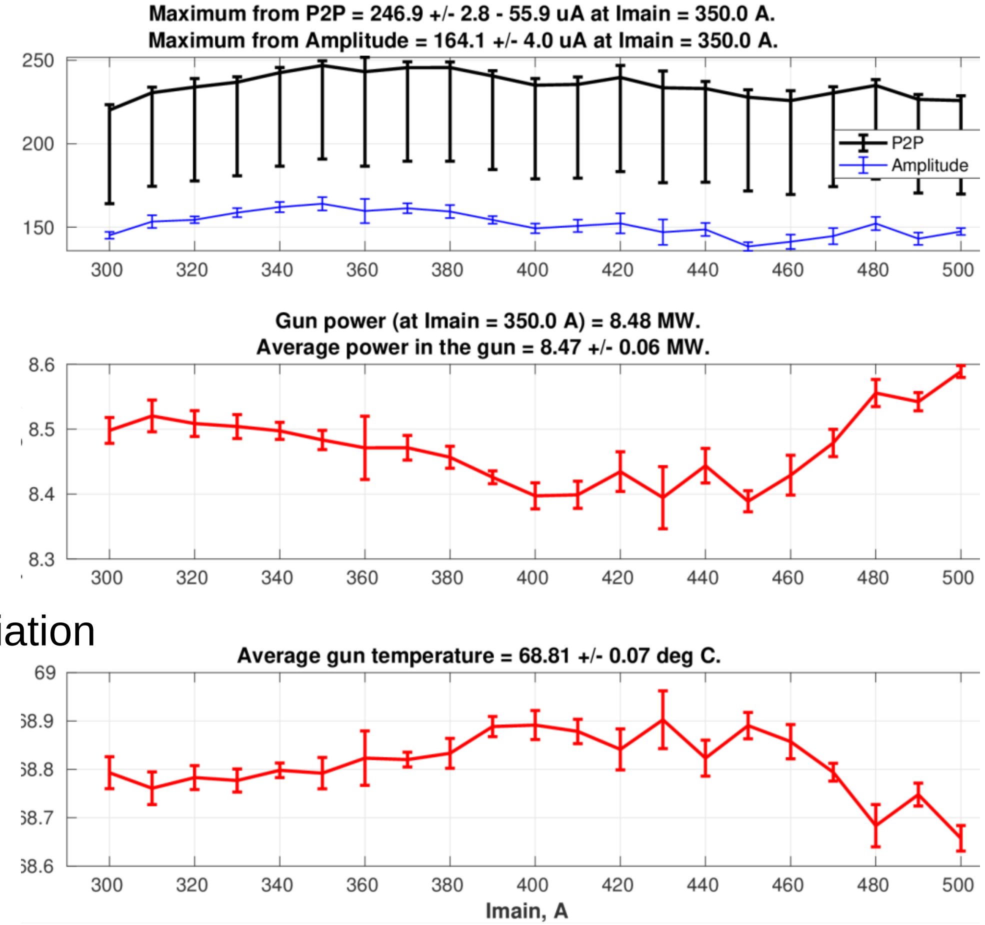
$\hbar\omega$ = photon energy (eV)



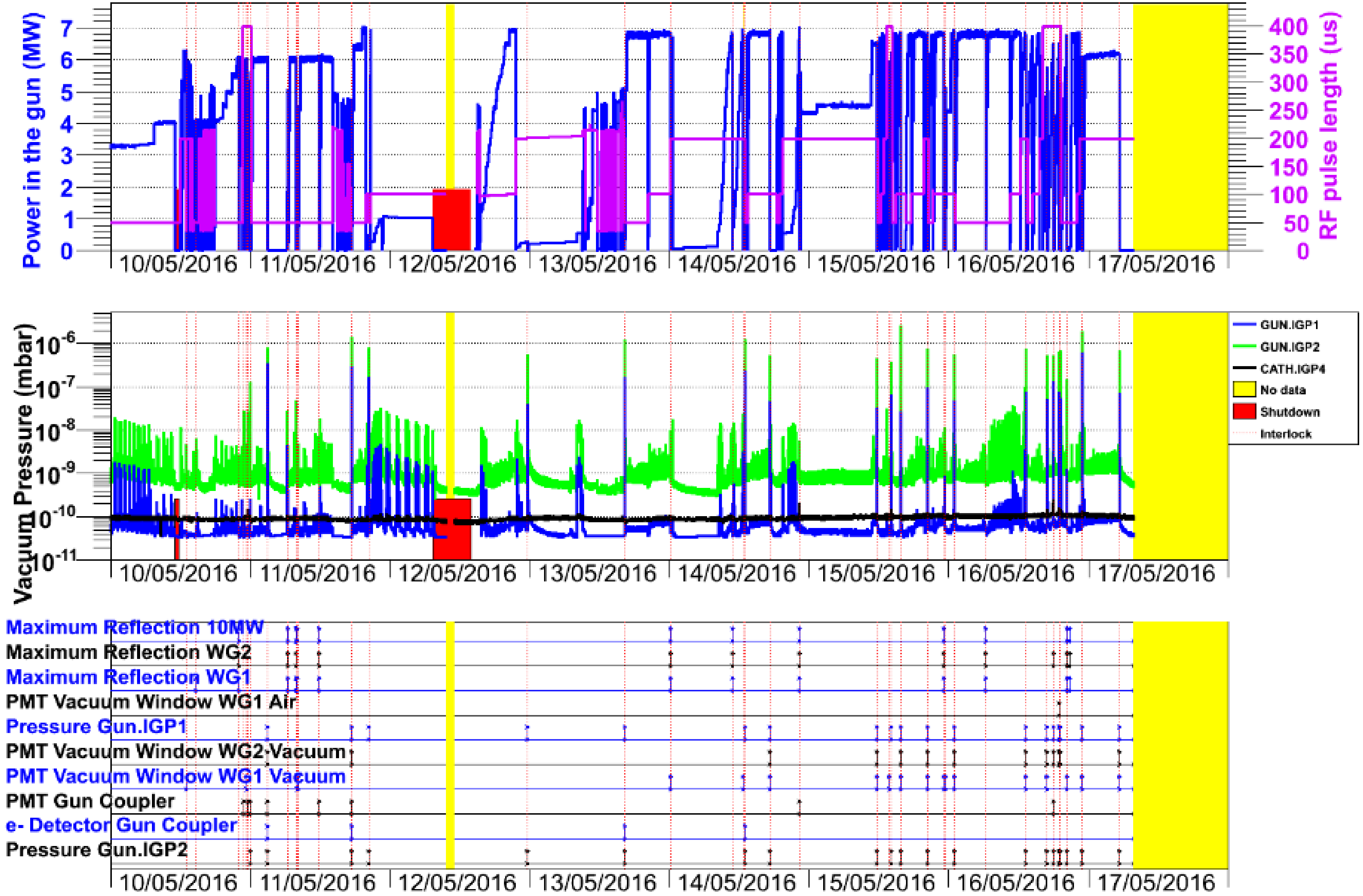
Dark current

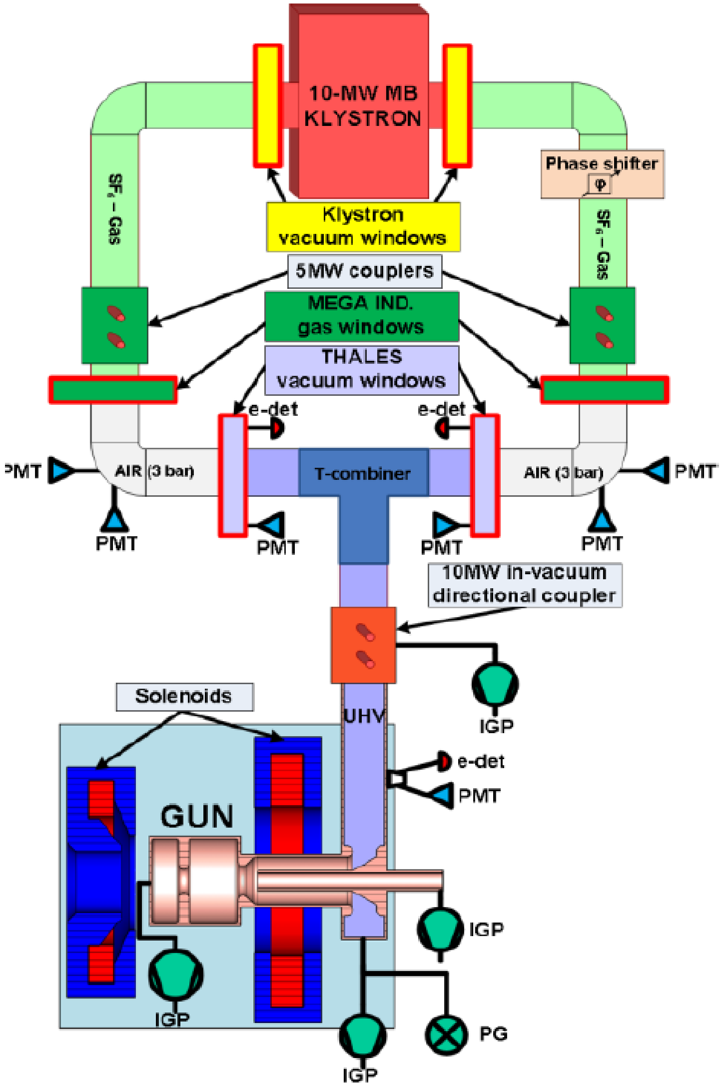
Dark current

- **Unwanted electrons** emitted without laser trigger
- **Main cause:** Field emission from high surface fields
- Follow Fowler–Nordheim behavior. $J \propto E^2 \exp(-B/E)$
- **Impact on Beam Quality**
  - Adds **uncontrolled background charge**.
  - Increases **beam halo** and **emittance.**
  - Can degrade **energy spread** measurements
- **Risks:** Radiation damage, heating of components
- **Diagnostics** – Detected using Faraday cups, BPM background, radiation monitors, or dark-current spectrometers
- **Mitigation**
  - Improve cathode and surface finish (polishing, coating)
  - Reduce peak field where possible
  - Use collimators and apertures to intercept unwanted electrons.
  - Conditioning of gun to lower emission sites



Example from gun conditioning



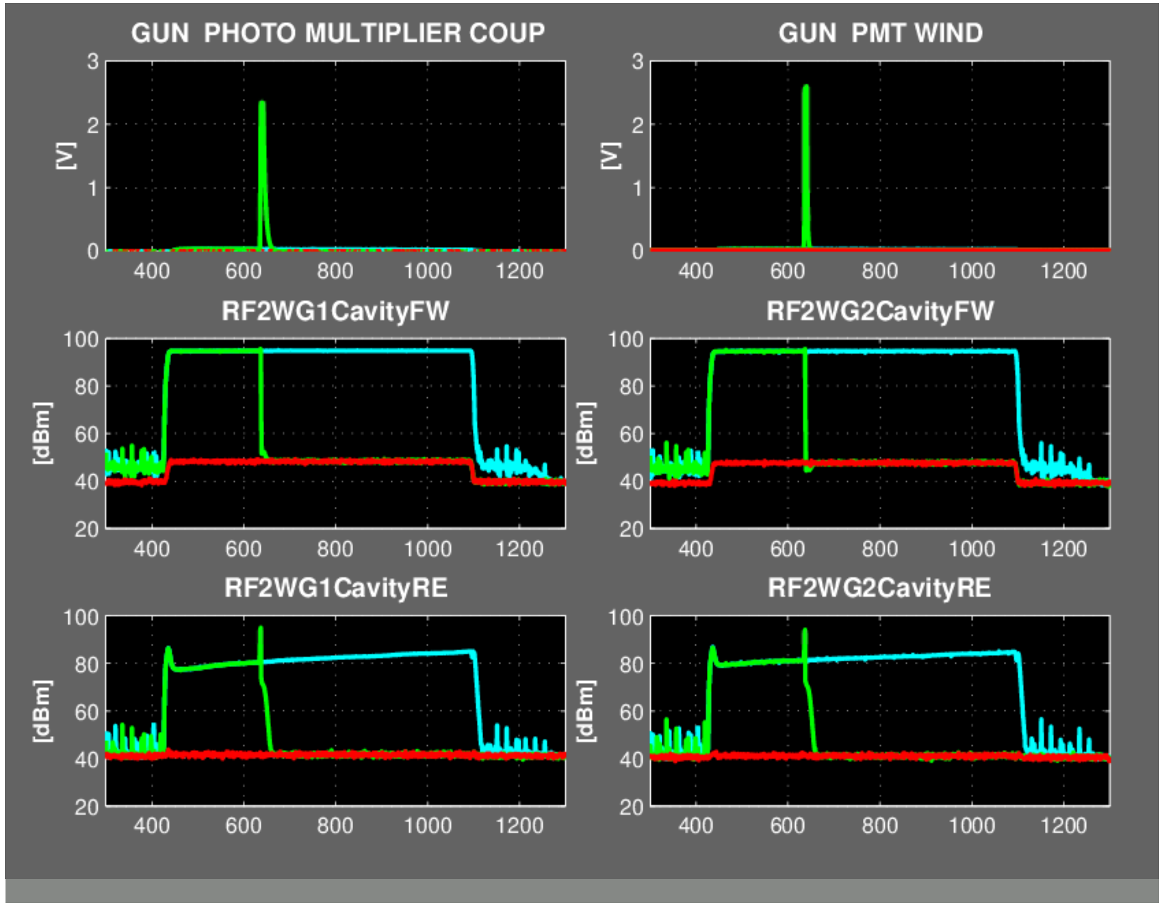


Interlock (IL) system at PITZ

- The PITZ gun IL system is designed to protect the accelerator from damage. It quickly stops the LLRF in case of e.g. sparks, light, RF or vacuum problems near the accelerating cavities.

- The PITZ IL system reaction time is in the range of a few microseconds → RF can be stopped within the RF pulse

- IL system collects signals from all IL devices and produces a common IL signal which stops the RF power.



Undisturbed RF pulse →

→ IL event detected →

→ RF pulse interrupted →

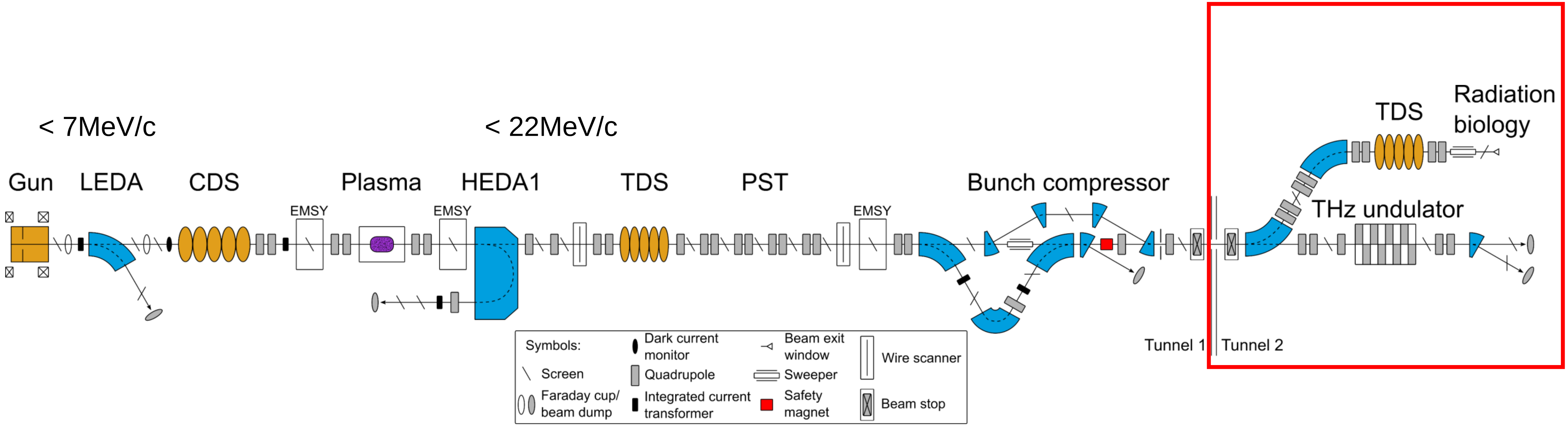
→ Signals after IL event (RF is off)

High brightness electron sources and their applications

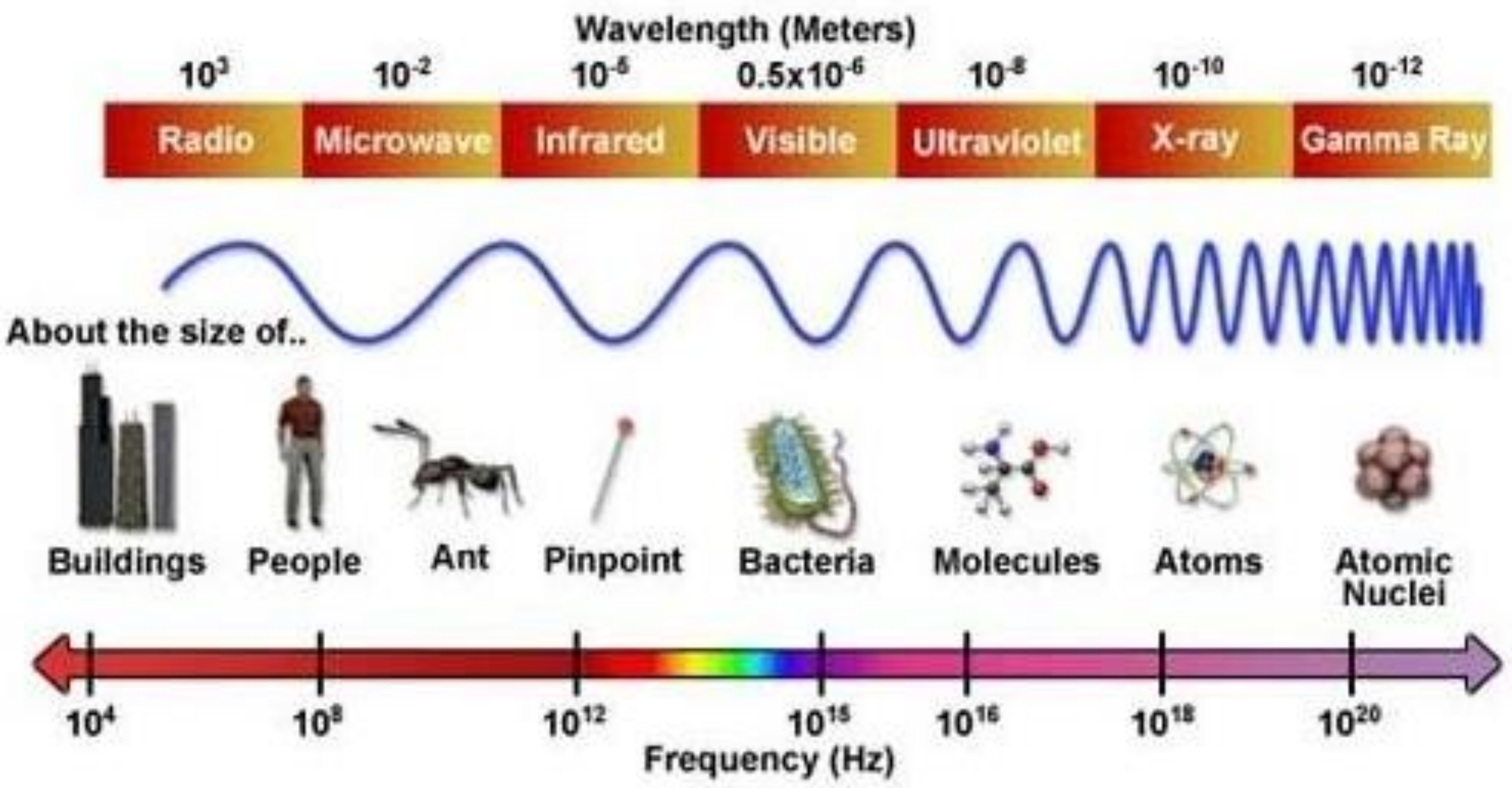
1. THz FEL

PITZ

Applications



Motivation

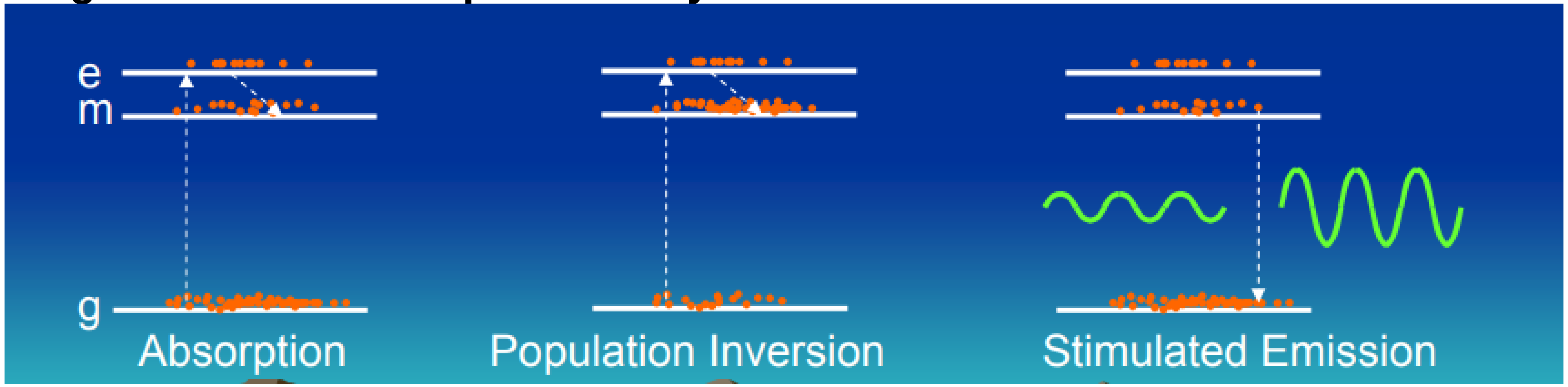


Exploration of matter
- Length scale → ~ Angstrom
- Time scale → ~ femtosecond

Quantum laser

Principle

- **Excitation:** External energy moves electrons from ground to excited states
- **Metastable state:** Electrons drop to a long-lived energy level → population inversion
- **Stimulated emission:** Incoming light triggers electrons to emit identical photons → light amplification
- Works with **bound electrons** in **atoms/molecules**
- Requires a **gain medium** and **optical cavity**



Short life time of inner electrons
Larger energy required to excite them

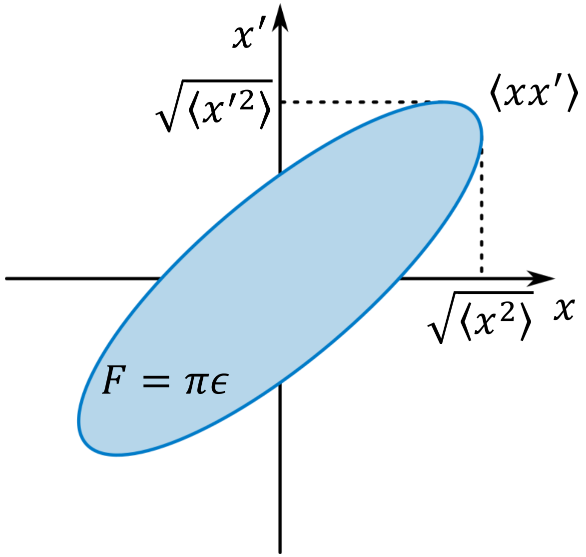
FEL differs because it uses free electrons in a magnetic undulator instead

Free-electron laser performance

Transverse emittance

- Volume in transverse phase space

$$\epsilon = \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$



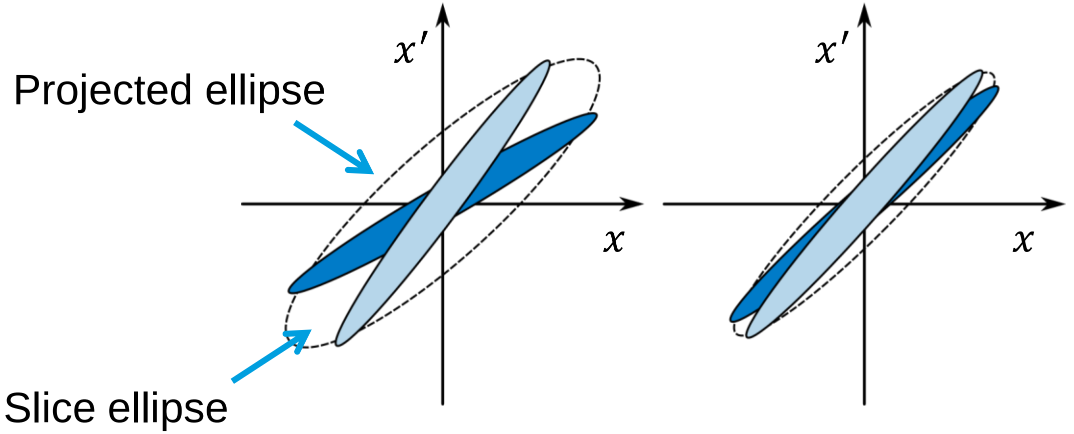
Emittance criterion: $\frac{\epsilon}{\beta\gamma} \leq \frac{\lambda_{\mathrm{rad}}}{4\pi}$ [1]

Beam phase space emittance

Radiation phase space volume

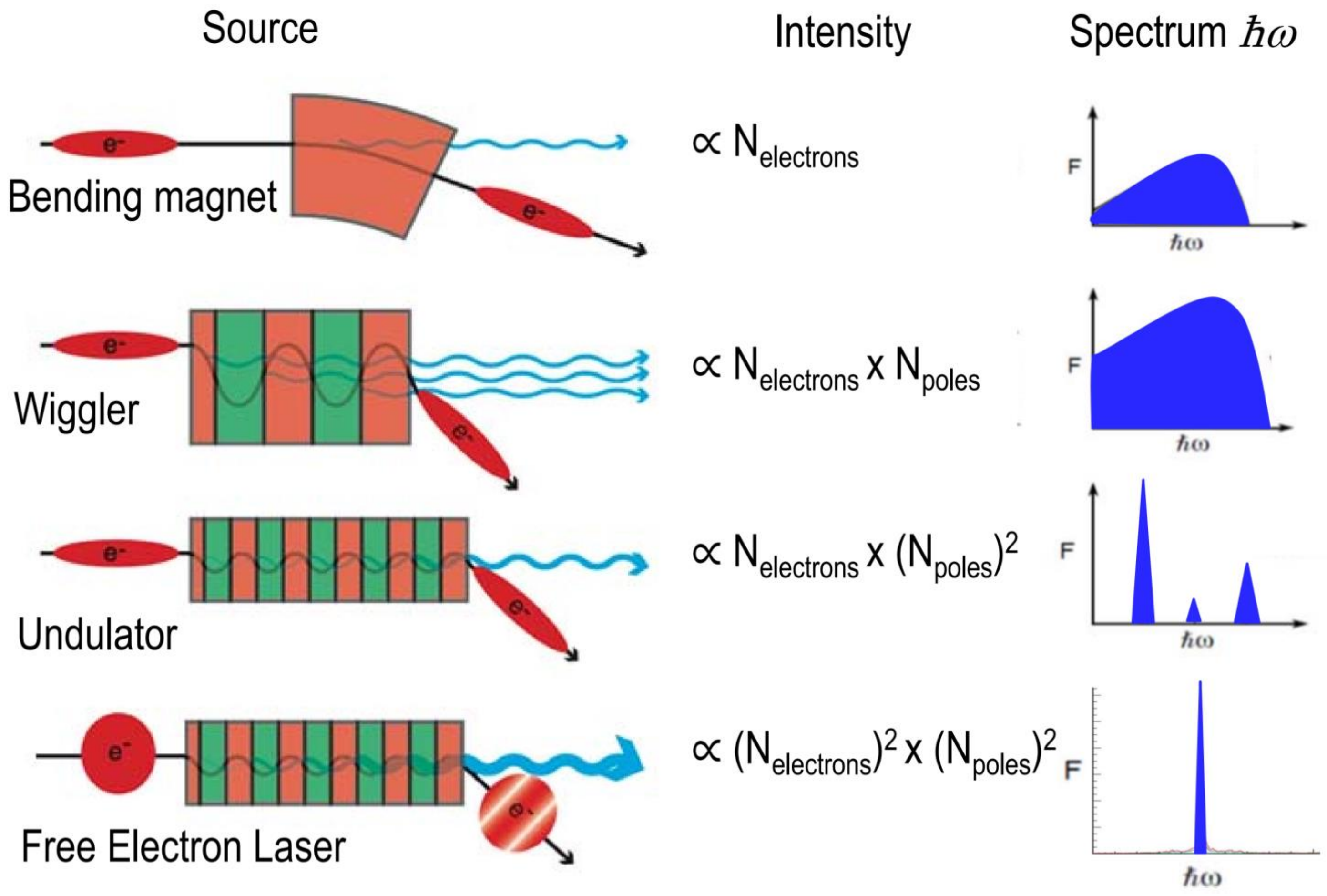
FEL process on fraction of bunch

- Slice emittance important
- *Slice matching* determines projected emittance



[1] P. Schmüser et al., Free-Electron Lasers in the Ultraviolet and X-Ray Regime, Springer (2014)

Light sources



single arc → wide spectrum → IR → X-ray (depends on γ, R)

many arcs → more flux, still broadband → IR → X-ray

coherent interference → narrow lines.

undulator + feedback → laser-like beam→ UV → hard X-ray

Motivation

A method for time resolved measurements

- Static
  - A continuous-wave (cw) laser is pointed on the sample and the output (spectrum, spatial distribution etc. is analyzed)
- Dynamic
  - A short pulse laser is used to investigate transient phenomena
- Pump-probe
  - 2 laser pulses are used*
  - The first laser pulse (pump) triggers a reaction from the sample
  - The second pulse (probe) is used to characterize the sample
  - The delay between the pulses is scanned to investigate sample dynamics (other properties e.g. pulse energies can be scanned, too)
  - The 2 pulses can come from the same laser or from different lasers (with different wavelengths)

Zhang, X., Shkurinov, A. & Zhang, Y. Extreme terahertz science. *Nature Photon* **11**, 16–18 (2017). https://doi.org/10.1038/nphoton.2016.249

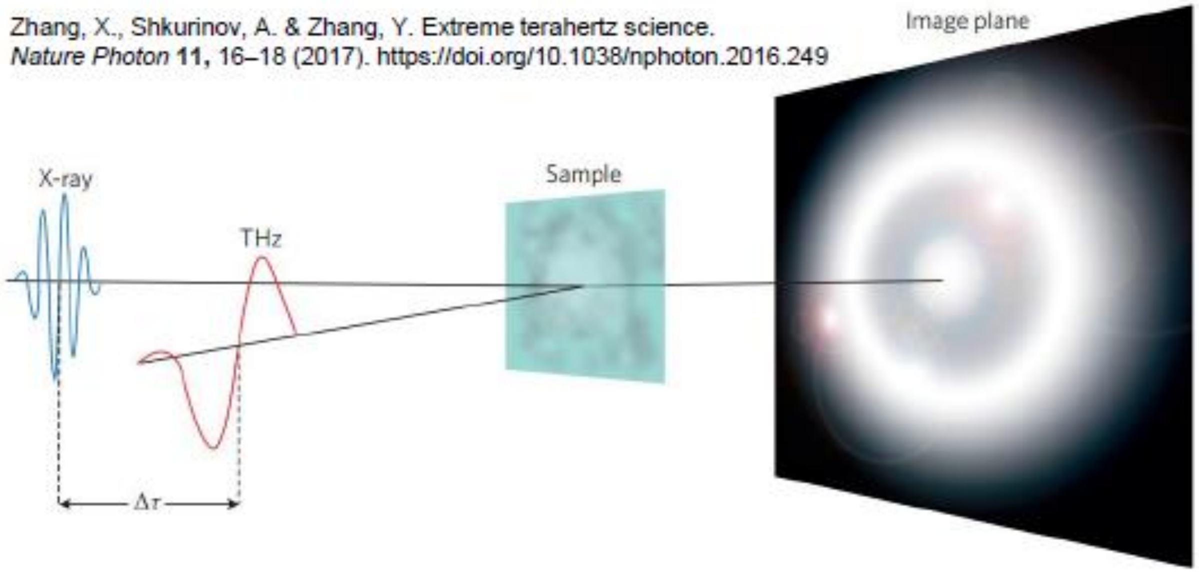


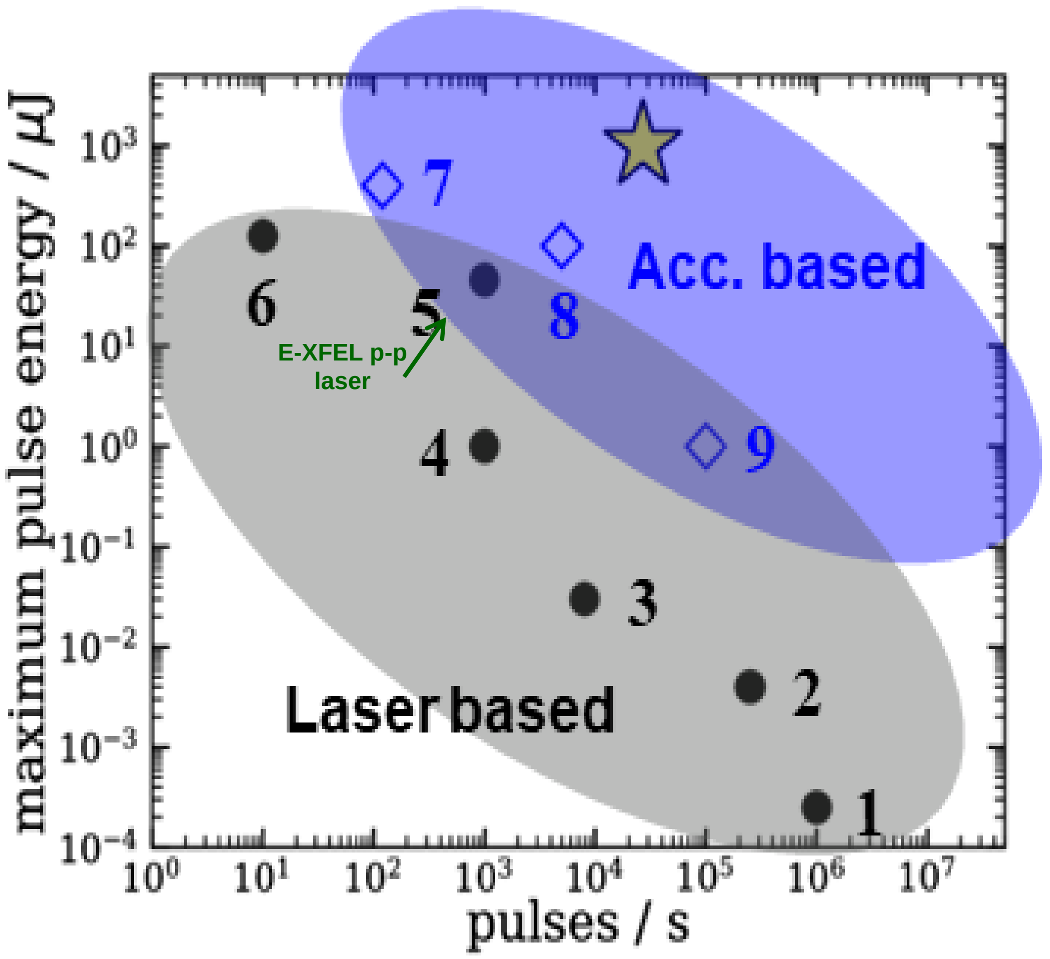
Figure 1 | Conceptual illustration of a pump-probe experiment employing a THz pump and an X-ray probe for time-resolved nanoscale imaging. The idea is to use the THz pulse as a pump to modify the atomic structure of a target and then capture an image of the atomic structure by X-ray scattering. Δτ is the timing between the X-ray pulse and the THz pulse.

THz Free Electron Laser

Laser based THz sources are limited at high repetition rate, while most IR/THz driven dynamics needs pulse energy above 1 μJ.

1,3,5,6 - Optical rectification [1]
2 - Photoconductive antenna [1]
4 - Two-color Laser filamentation [2]
7 - CTR (LCLS/FACET) [3]
8 - UR (FLASH) [4]
9 - UR (TELBE) [5]

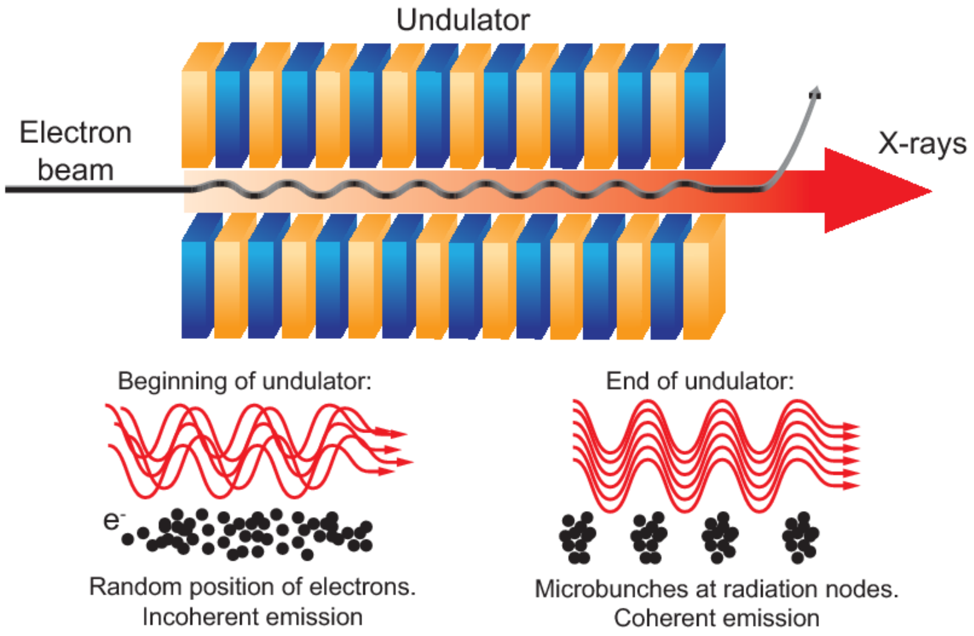
[1] B. Green, et al, Sci.Rep.V. 6, Article number: 22256 (2016)
[2] M. Gensch, Proceedings of FEL 2013, 474 (2013)
[3] T. I. Oh et al 2013 New J. Phys. 15 075002
[4] https://flash.desy.de/
[5] https://www.hzdr.de/db/Cms?pOid=34100&pNid=2609&pLang=en



Free Electron Laser

Basic principles

In a free-electron laser (FEL), the magnetic field of the undulator magnet causes the electrons to oscillate transversely and at resonant wavelength λ_{rad}



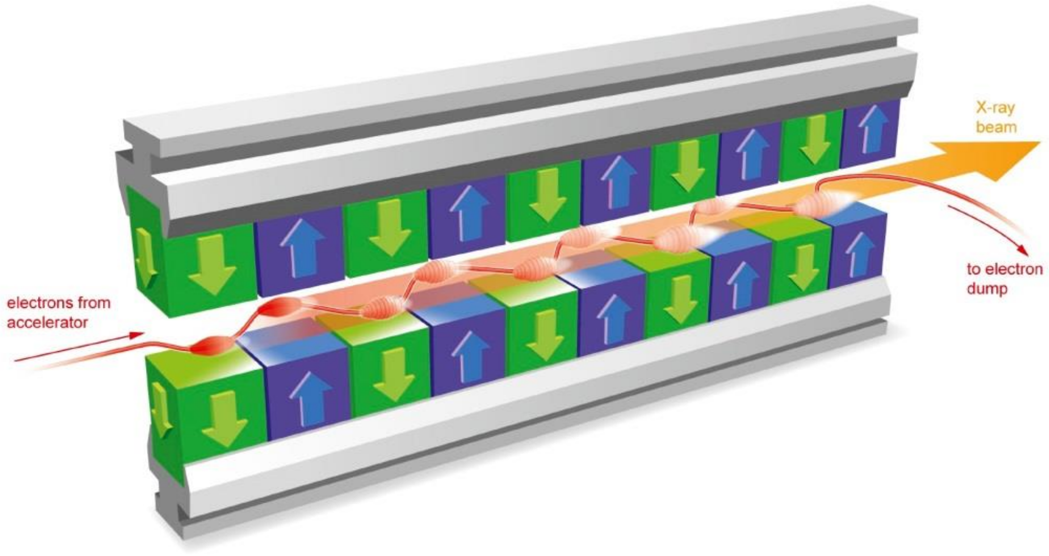
$$\boldsymbol{\lambda_{rad} = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)}$$

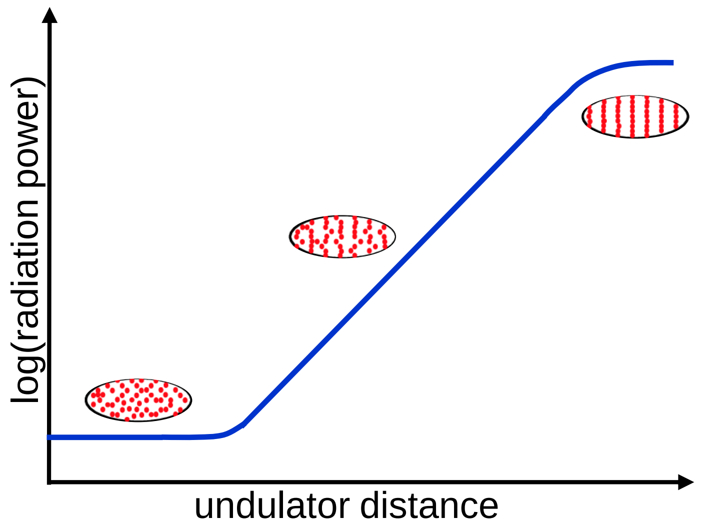
$$K = \frac{eB_0\lambda_u}{2\pi mc}$$

These oscillations induce **micro-bunching** on a scale of λ_{rad}, which causes electrons within the micro-bunch to radiate **coherently** at the resonant wavelength.

Free Electron Laser

Basic principles





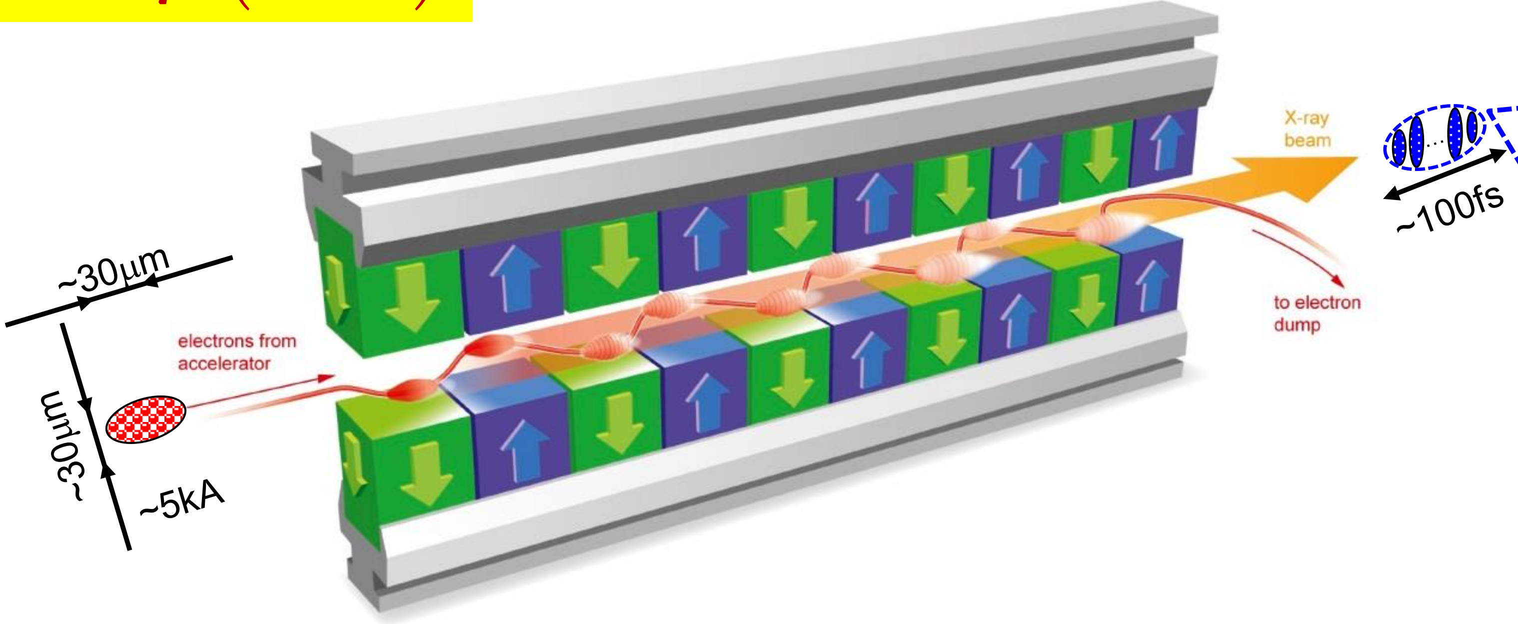
The process is referred to as **S**elf-**A**mplified **S**pontaneous **E**mission (**SASE**).

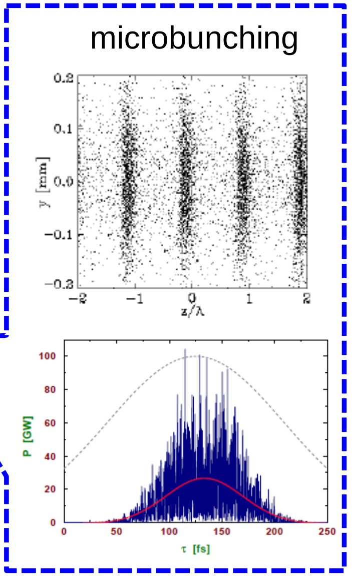
…starting from the shot noise!

X-Ray Free Electron Laser (XFEL)

SASE = Self Amplified Spontaneous Emission

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





E-beam brightness

$$B \propto \frac{2I}{\varepsilon_x \varepsilon_y}$$

The European XFEL, SASE-1: λ_u = 40 mm, E = 17.5 GeV, **λ=0.1 nm**

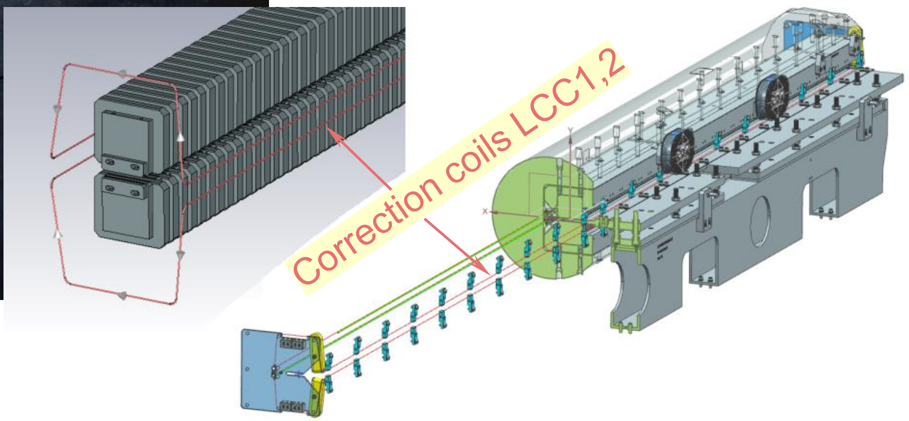
Proof-of-principle experiment on THz SASE FEL at PITZ

Using LCLS-I undulators (available on loan from SLAC)

Some Properties of the LCLS-I undulator

Properties	Details
Type	**planar hybrid** (NdFeB)
K-value	3.585 (3.49)
Support diameter / length	30 cm / 3.4 m
Vacuum chamber size	**11 mm x 5 mm** W
Period length	30 mm
Periods / a module	113 periods

PITZ+ LCLS-I Undulator

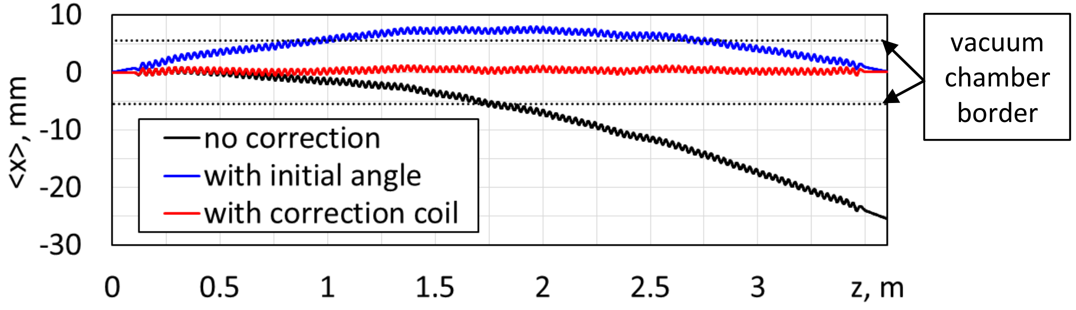


λ_{rad}~100μm → ~**17MeV/c**

Main challenges:

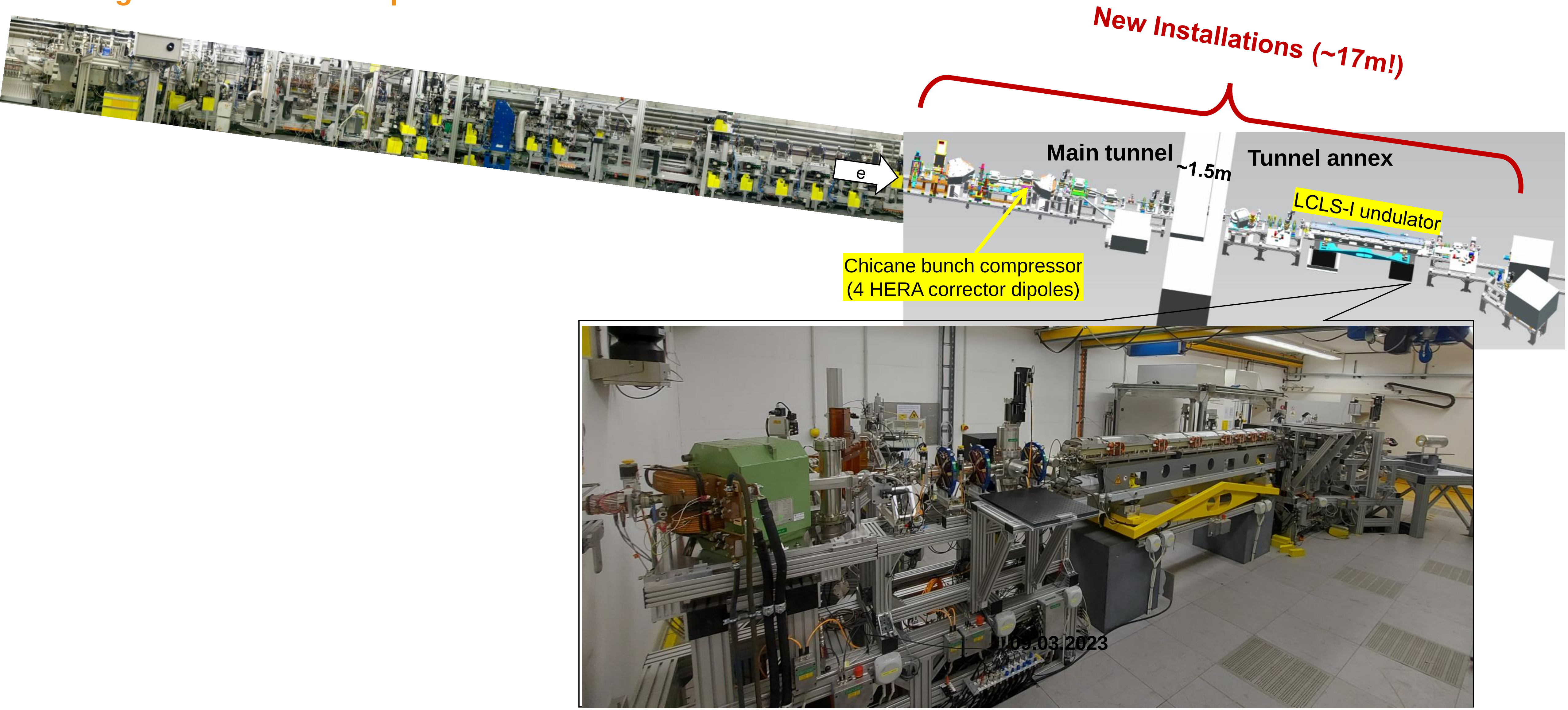
- Space charge effect
- Strong undulator (vertical) focusing + horizontal gradient
- "Full physics" might have to be considered
- Waveguide effect W
- Wakefields: geometric and conductive wall effects

Reference particle trajectories in the undulator with horizontal gradient



PITZ upgrade for the proof-of-principle experiment on THz source

Design and technical Implementation

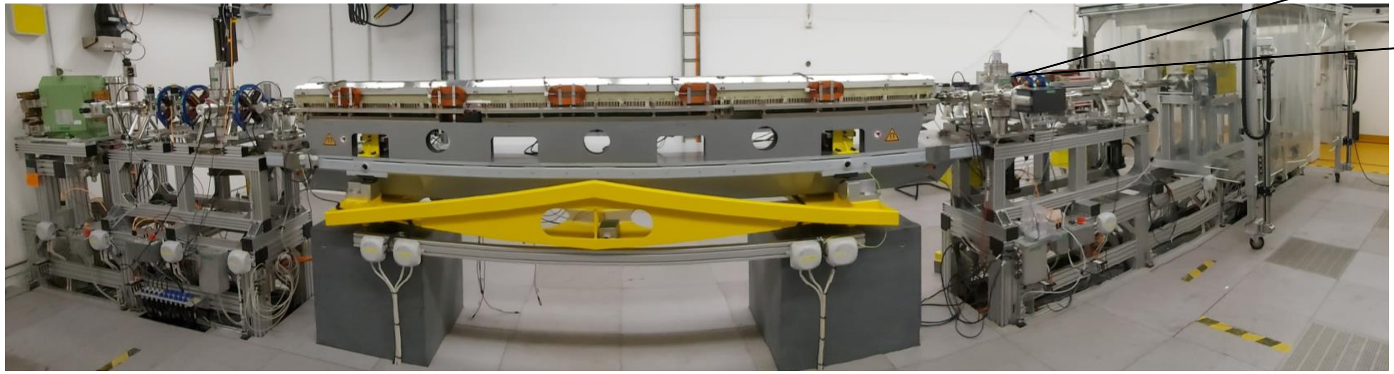


THz SASE FEL at PITZ

First Lasing on 09.08.2022

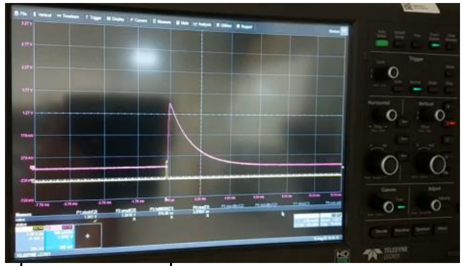
NB: SASE=start from noise

Pyroelectric detector

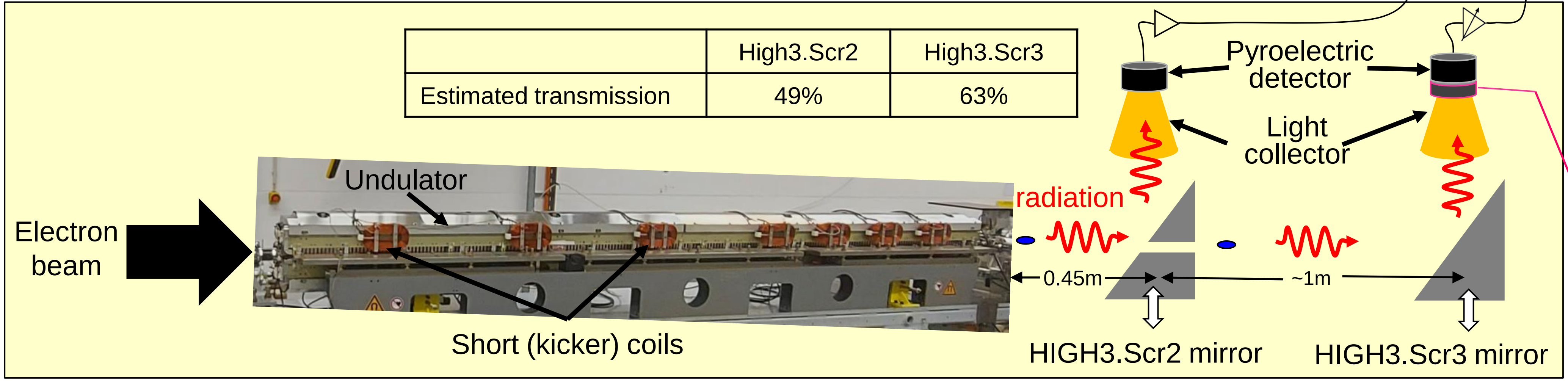


THz SASE FEL at PITZ: THz diagnostics setup

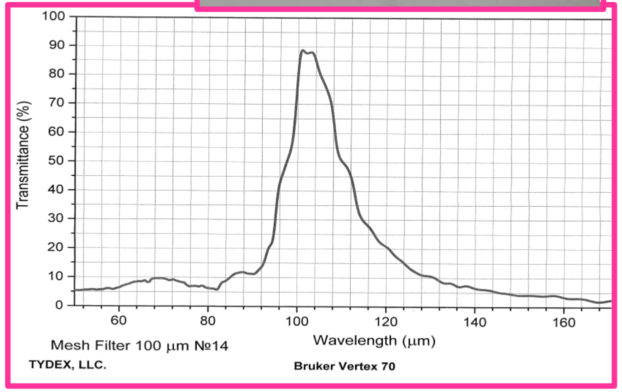
Startup: pyroelectric detectors with collector cones



	High3.Scr2	High3.Scr3
Estimated transmission	49%	63%

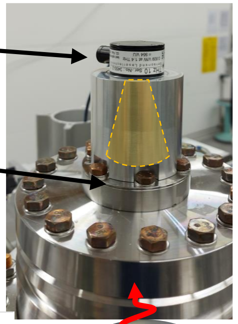


Band-pass filter
BPF3.0-24
λ_0~102μm; $\delta\lambda$~12μm
<f>~3THz

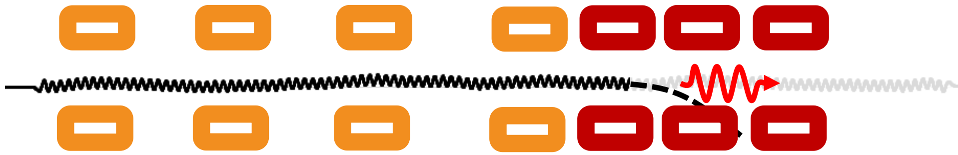


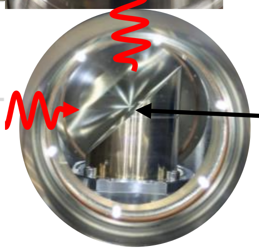
Pyroelectric detector THz10

Diamond 20mm viewport



Simplified layout of the gain curve measurement setup



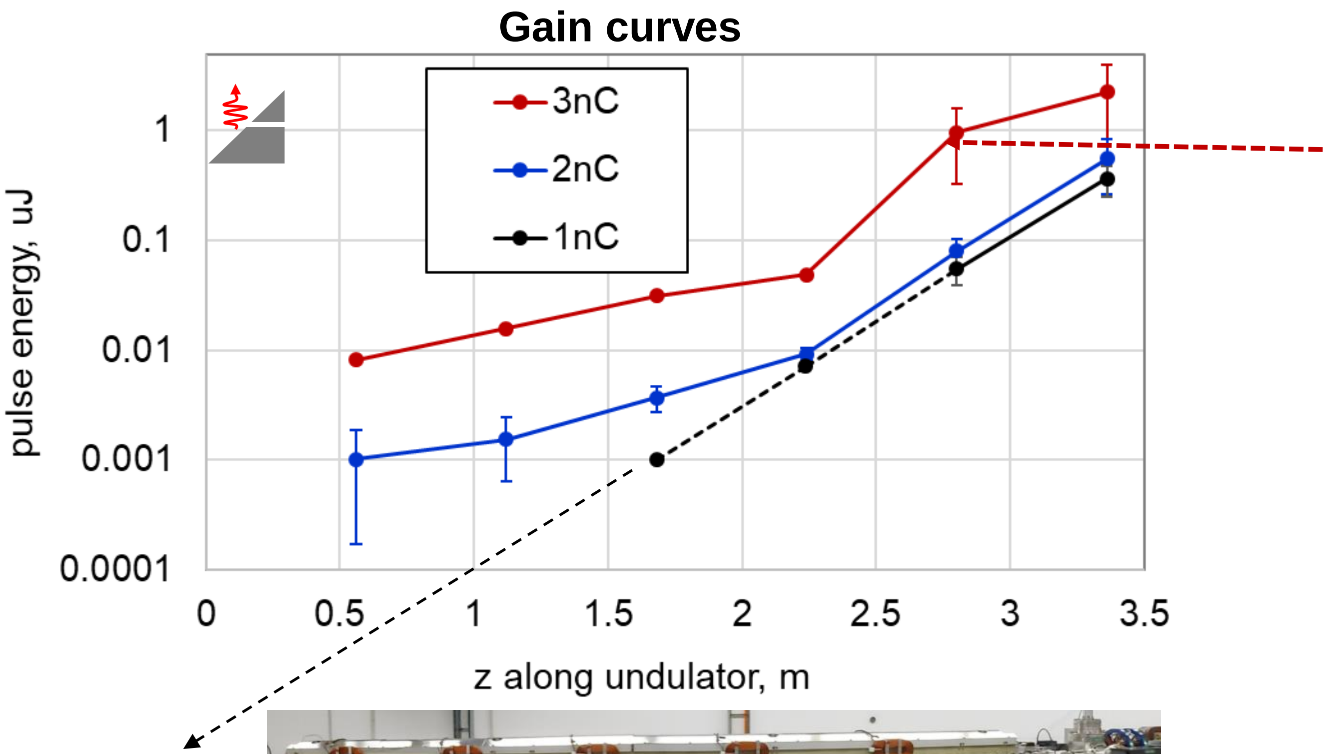


In-vacuum mirror

THz SASE FEL at PITZ: Gain Curves

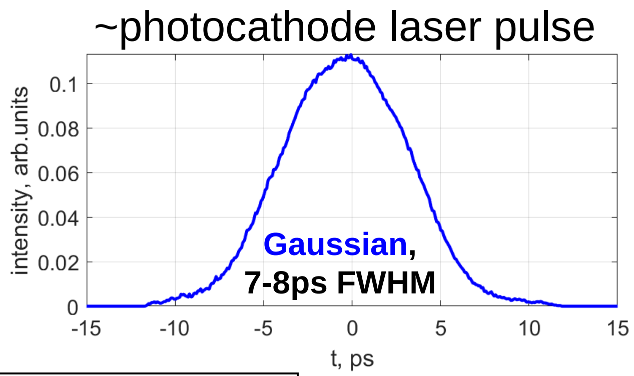
First Lasing Characterization

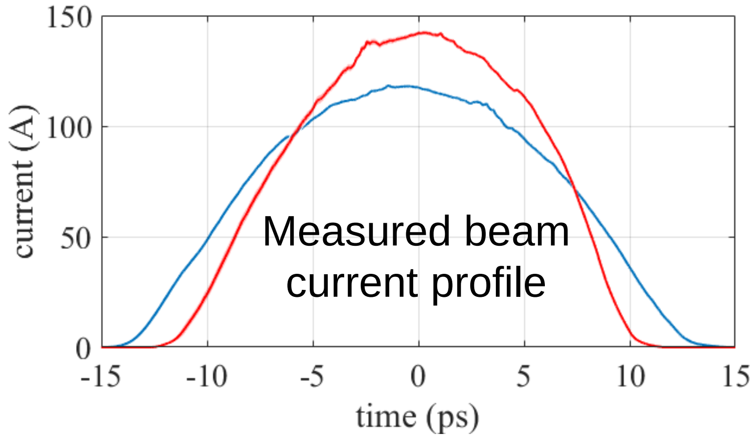
- Gain curves at 1nC, 2nC and 3nC for HIGH3.Scr2:
  - in-vacuum mirror with hole
  - No band-pass filter (BPF)
- **Lasing at ~100µm ➔ high gain THz SASE FEL at PITZ!**

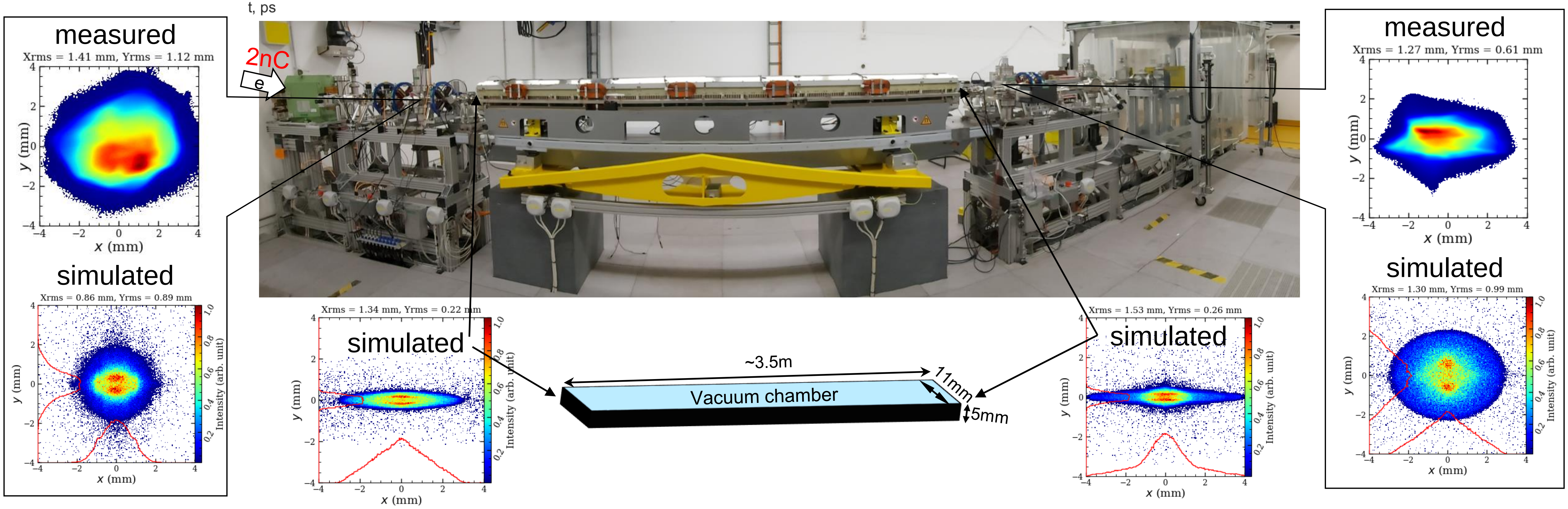


THz SASE FEL at PITZ

Electron beam matching (2nC) for lasing

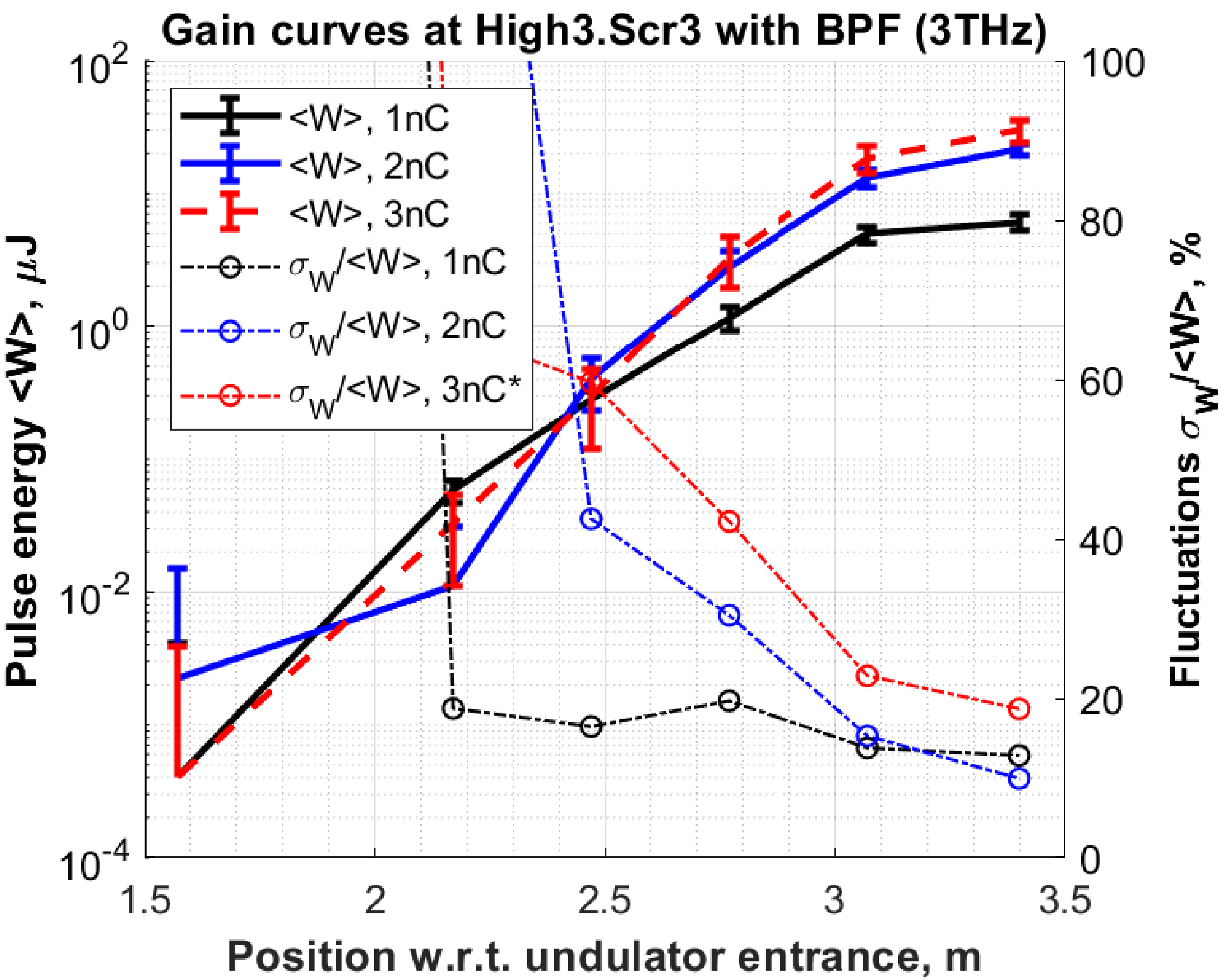




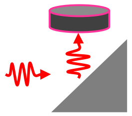


SASE Gain Curves at High3.Scr3 with BPF

In-vacuum mirror without hole + 3THz Band-pass filter



Optimization progress
<pulse energy> (fluctuations)
High3.Scr2 vs High3.Scr3



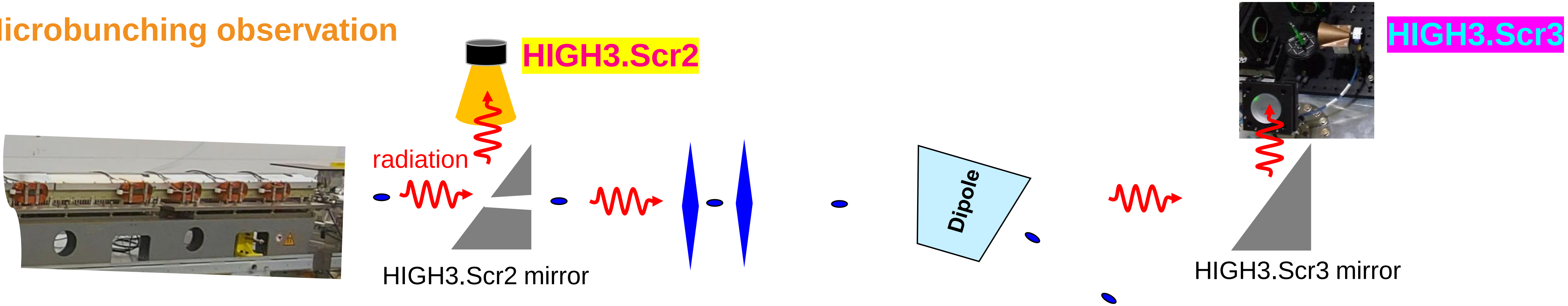
Bunch charge	1st lasing, no BPF	Tuning, BPF
1nC	0.36 uJ (32%)	6.12uJ (13%)
2nC	0.55uJ (52%)	21.44uJ (10%)
3nC*	2.26uJ (78%)	29.67uJ (19%)

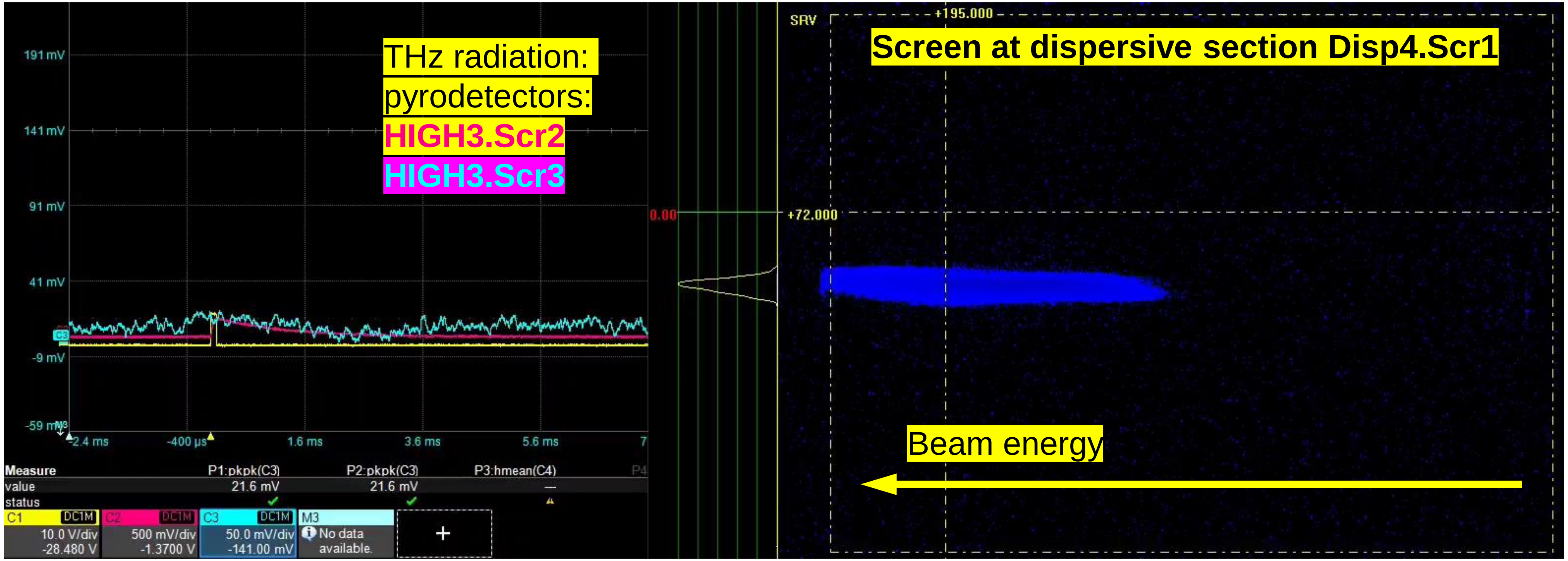
* Not fully optimized

NB:
- Calculations for the BPF (λ_0~102μm) → <Pz>~16.5MeV
- Experimentally → <Pz>~17MeV/c

Correlation beam@Disp4.Scr1 and pyro signals observed

Microbunching observation

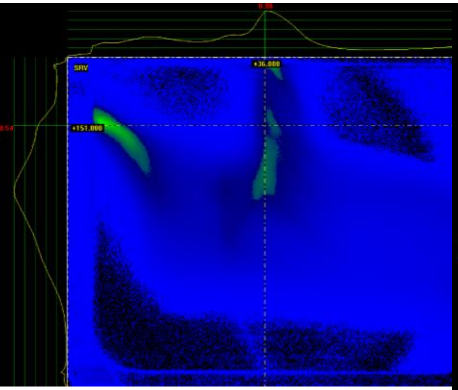


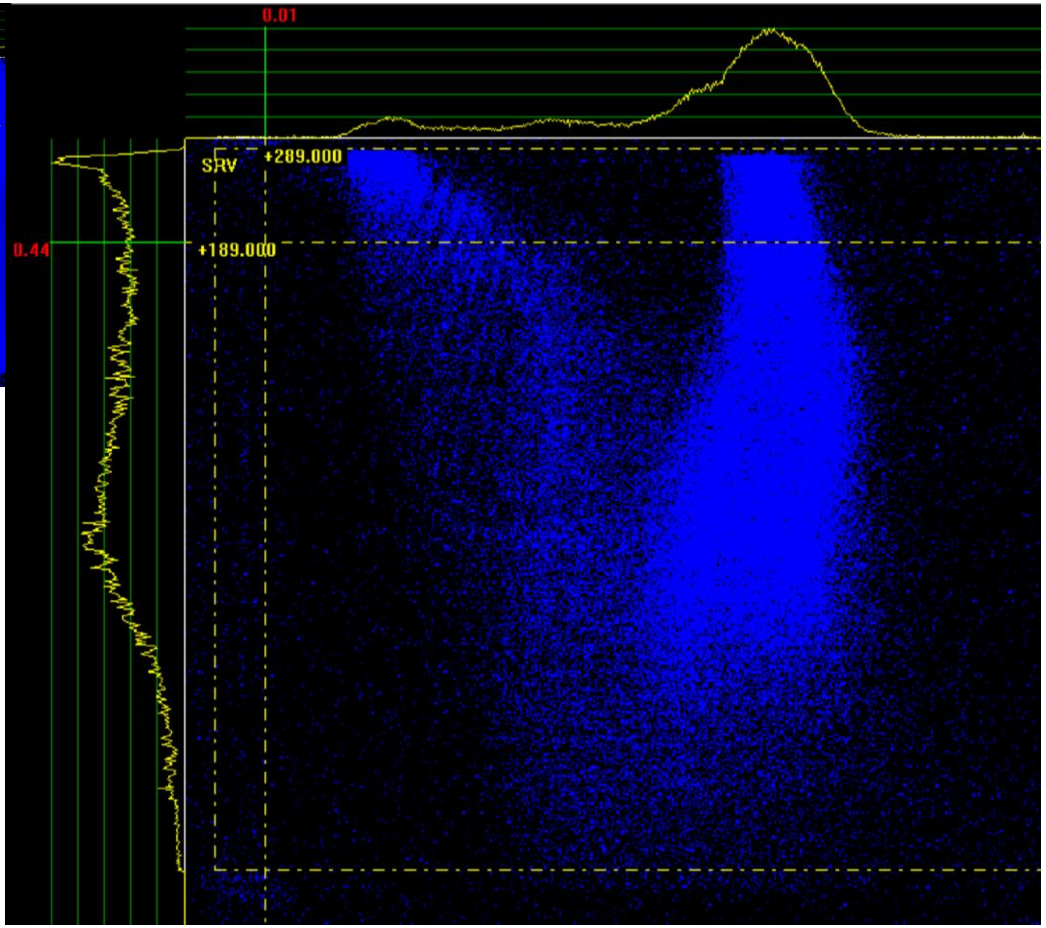


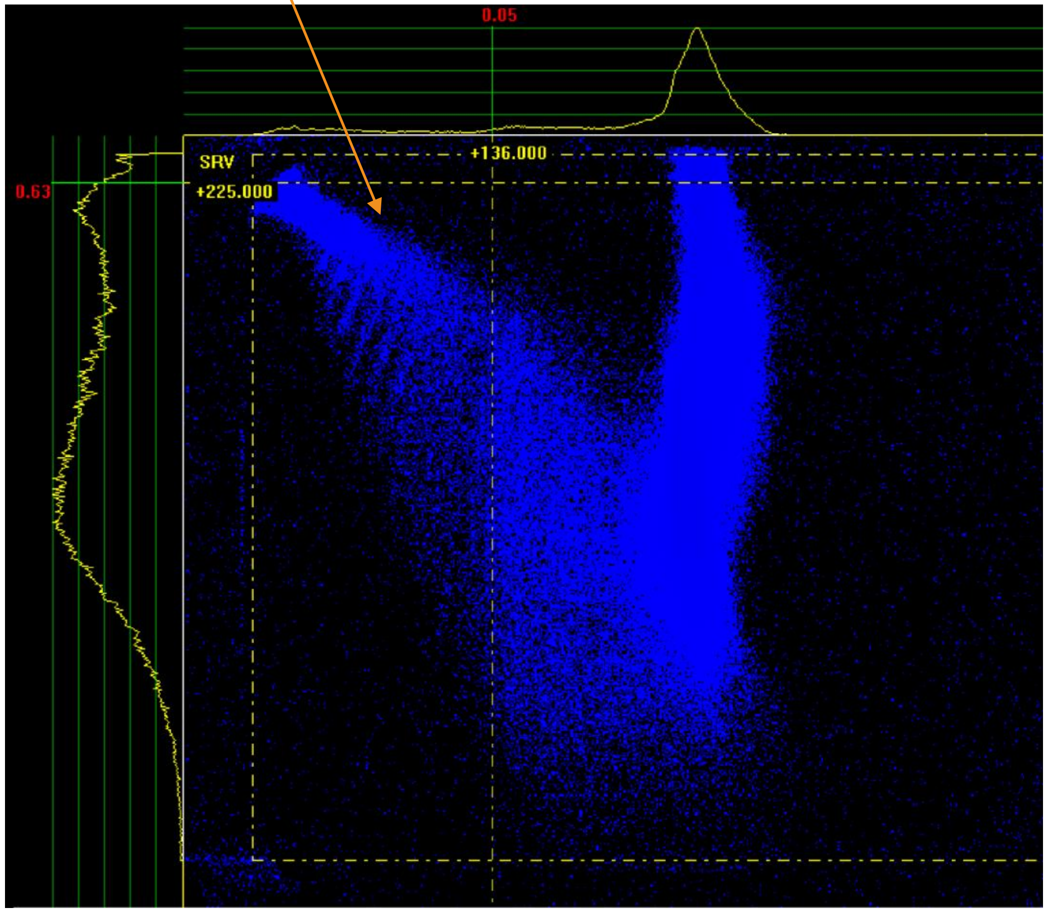
Disp4.Scr1

(After-)Lasing beam in horizontal dispersive arm

Microbunching?



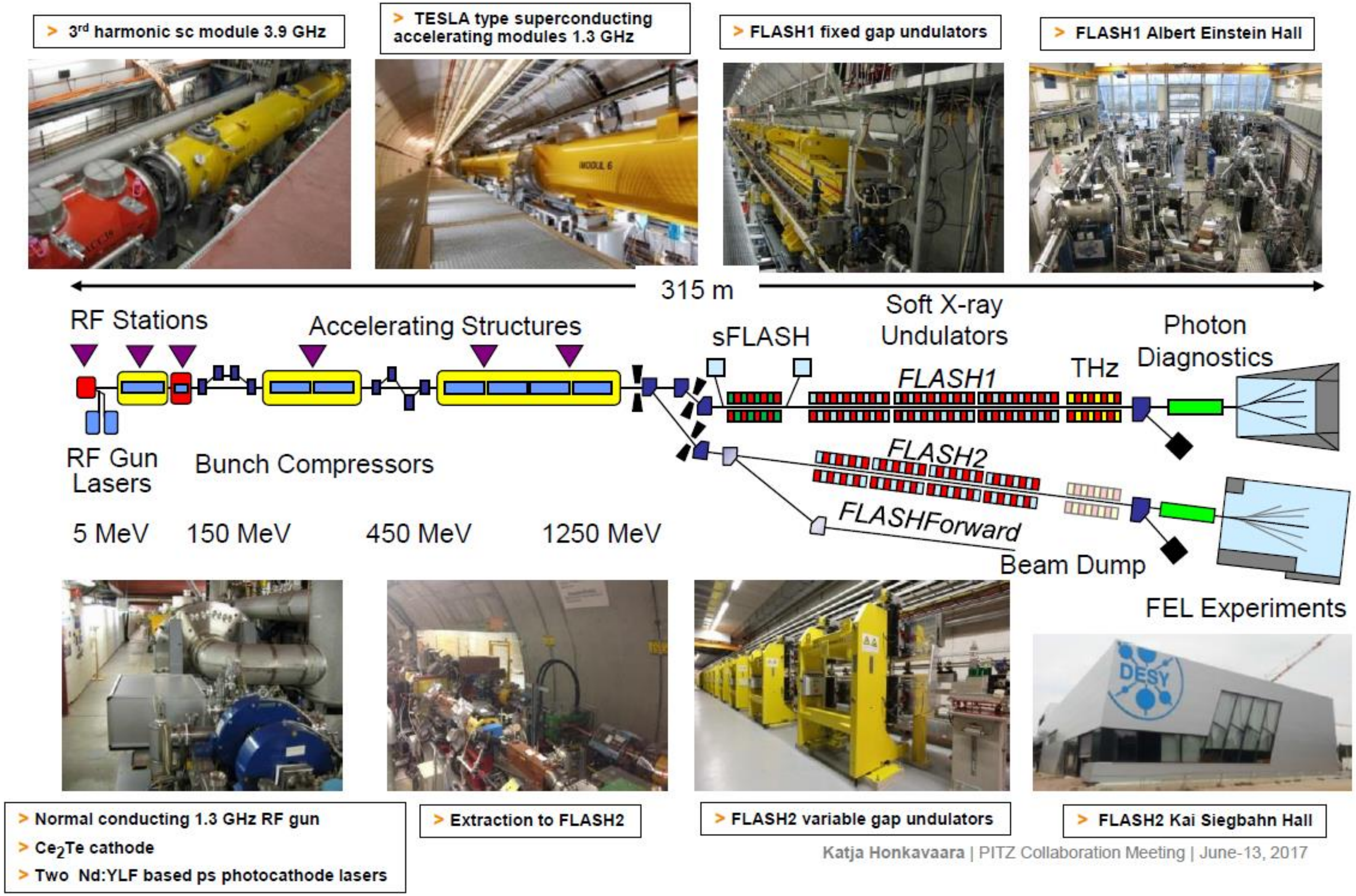




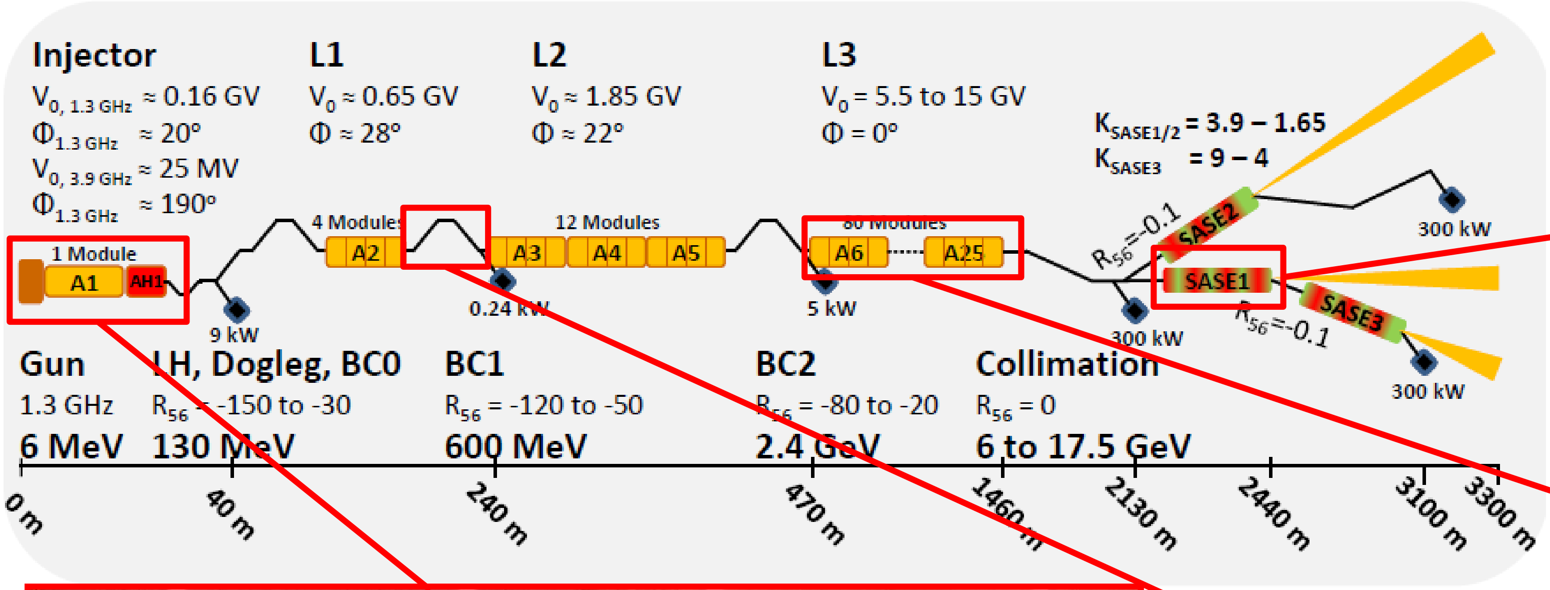
FLASH

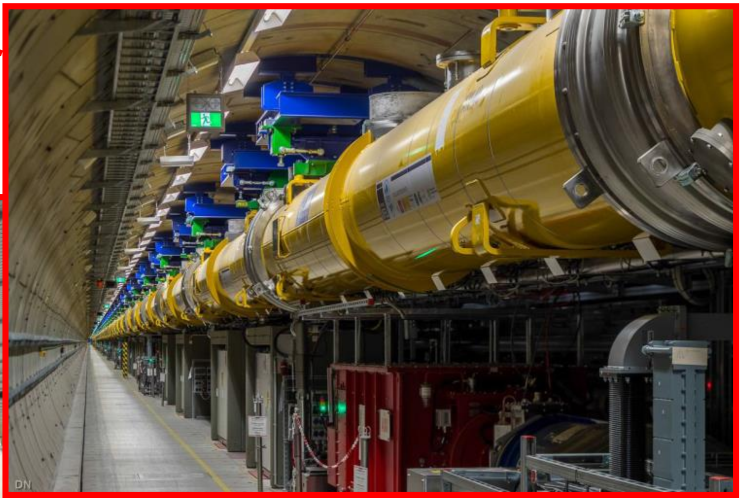
- FLASH is a free-electron laser (FEL) facility at DESY that produces ultra-short and intense XUV and soft X-ray pulses. The photon energy at FLASH ranges from 14 to 370 eV depending on the wavelength and the beamline

$$E = \frac{hc}{\lambda}$$



European XFEL





The European XFEL reached a world record photon energy of **25 keV** in 2020, corresponding to a wavelength of 0.5 Angstroms. The facility can operate at photon energies from 0.25 to 25 keV

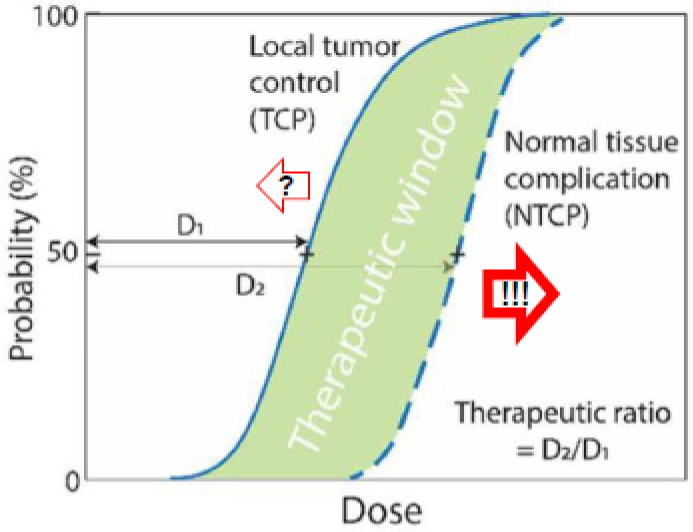
High brightness electron source applications

2. Flashlab at PITZ

What is FLASH radiation therapy ?

FLASH effect is an experimental observation (Favaudon, 2014), underlying mechanism still under study

- Medical/biological definition of the FLASH effect (in vivo):
  - Sparing of healthy tissue by radiation with short, high intensity pulses (e^-, p, ion, x-ray) while having at least the same tumor control as with conventional radiation



Basic sketch from M.R. Ashraf et al., Frontiers in Physics, 2020, doi: 10.3389/fphy.2020.00328

→ Opening therapeutic window

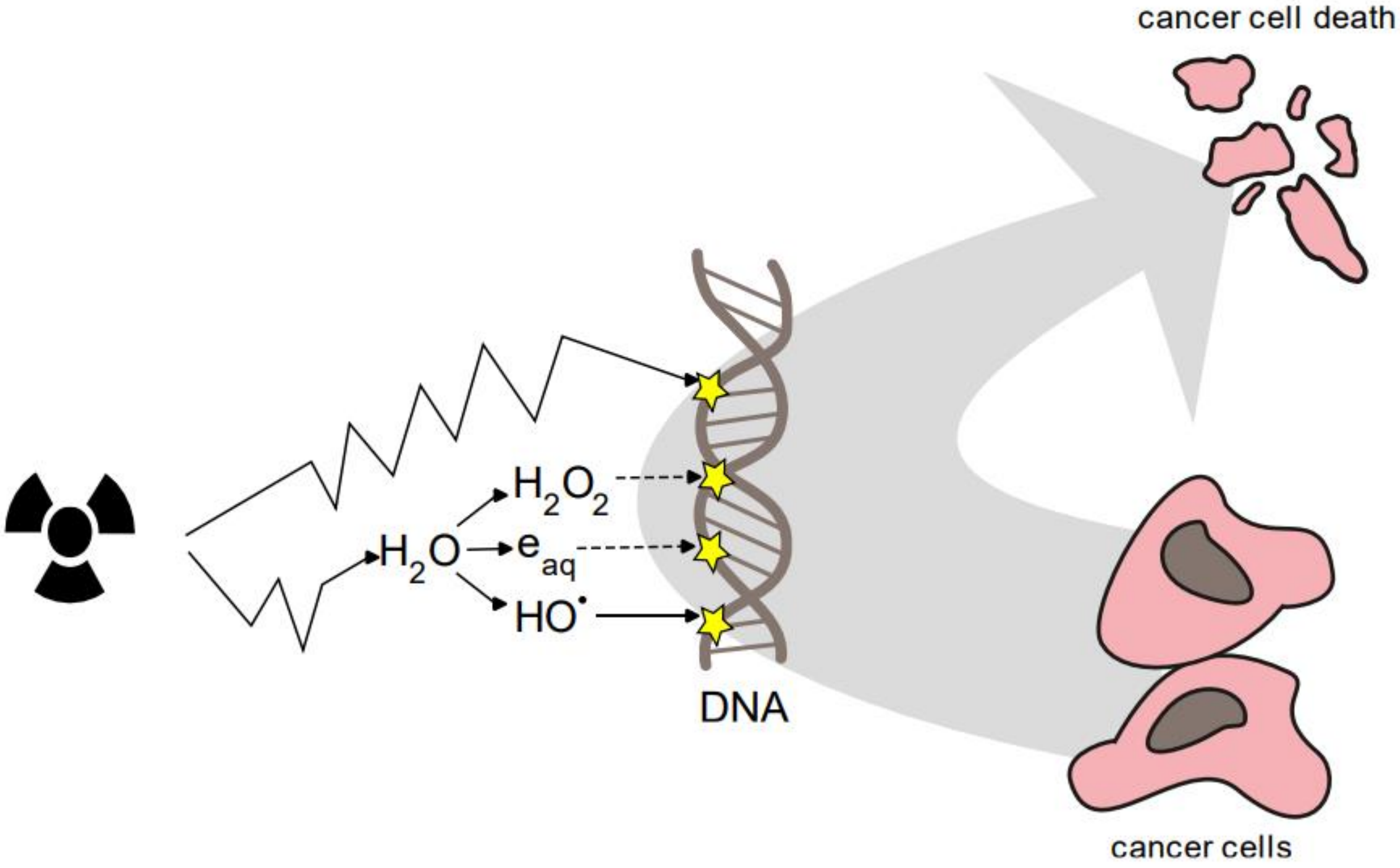
→ Strongly reduce treatment time, simply life for patients

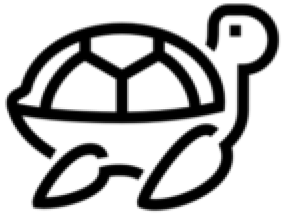
→ Treating radiation resistant cancer

→ With online imaging (e.g. via XFI): confine dose to moving cancer (e.g. lung)

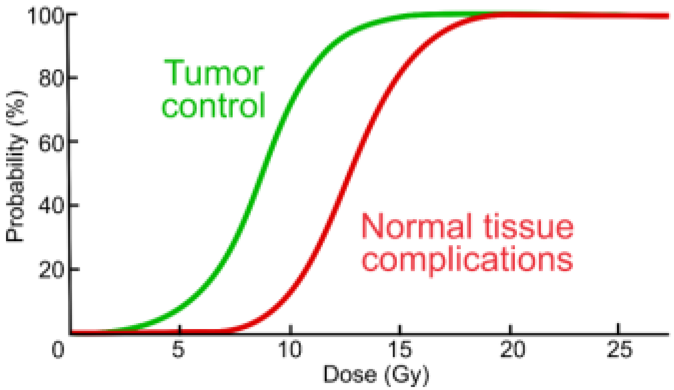
Dose: absorption of one joule of radiation energy per kilogram of matter
Dose rate: A dose rate is quantity of radiation absorbed or delivered per unit time (µGy/h)

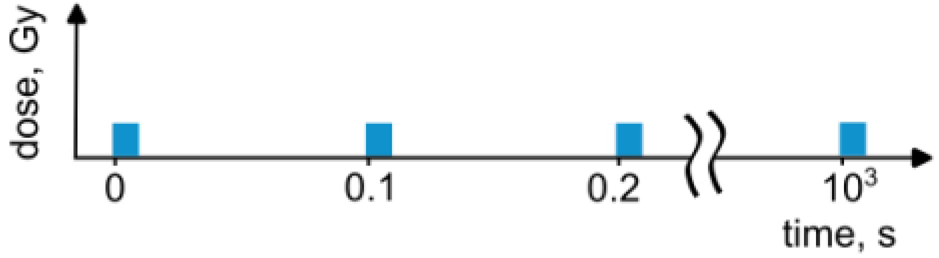
Conventional RT





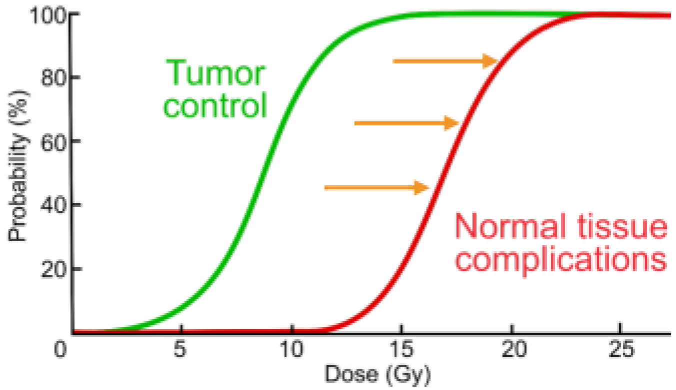
Conventional RT

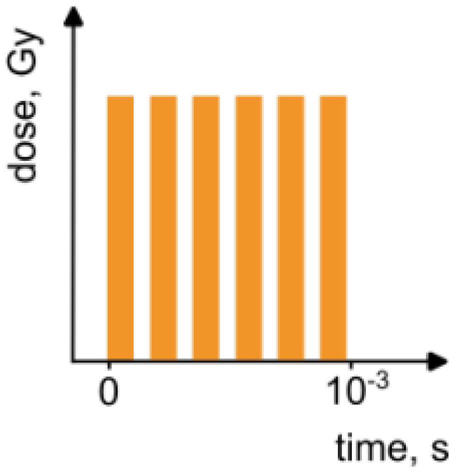




0.05 Gy/s

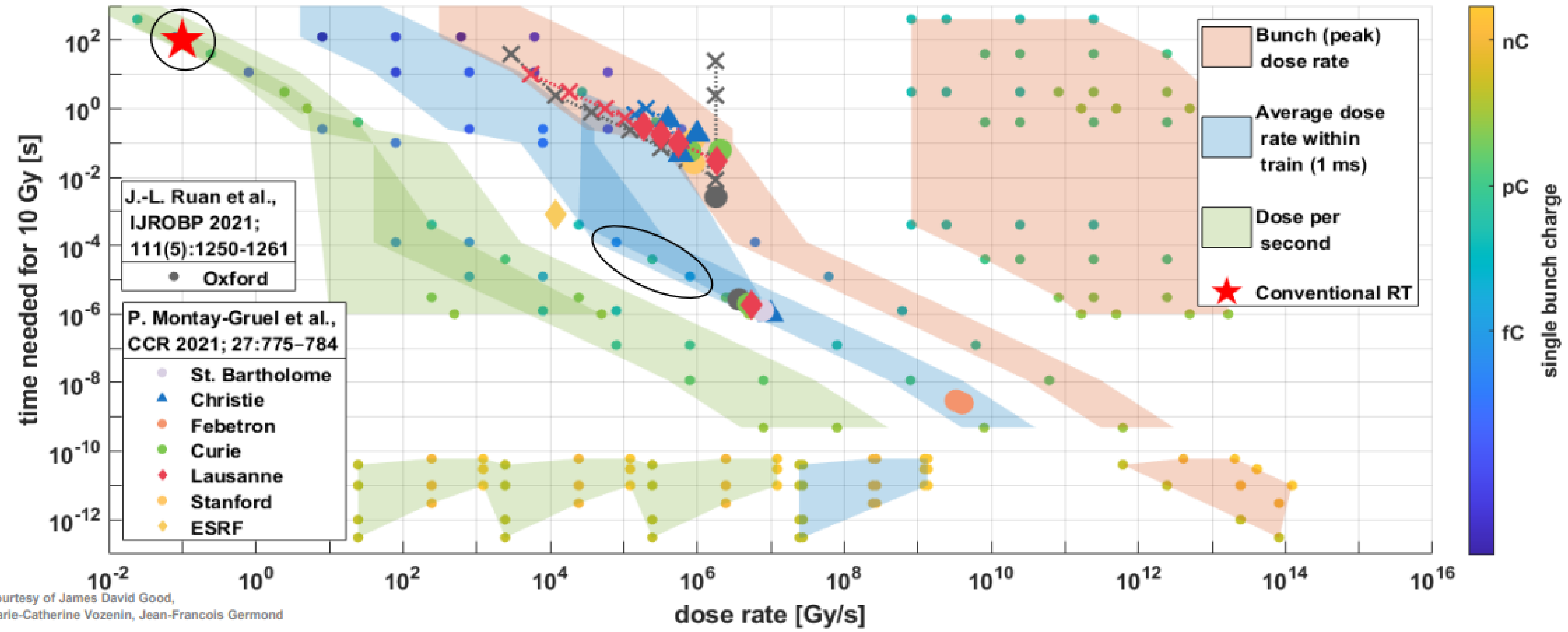
FLASH RT





10^6 Gy/s

Worldwide unique parameter space available @PITZ



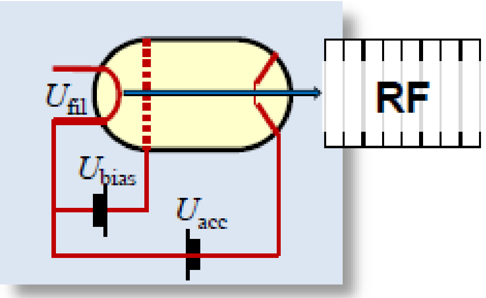
Courtesy of James David Good, Marie-Catherine Vozenin, Jean-Francois Germond

Definition of relevant beam parameters

Electron source type has key impact on the achievable beam parameters

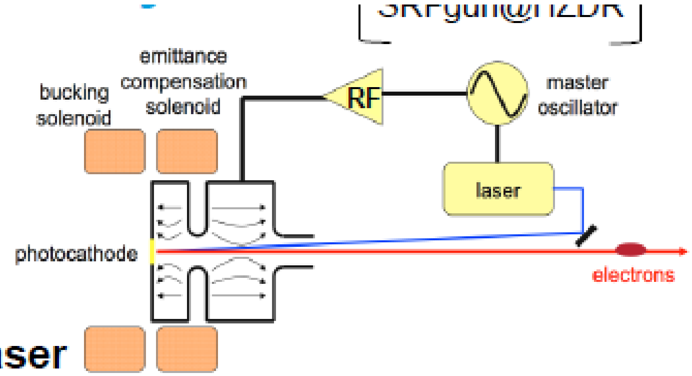
Standard:

thermionic electron source



- Heating + **grid** defines **length** of radiation pulse
- **RF frequency** of accelerating cavity defines **micro structure** inside radiation pulse

High brightness photo injector:



- Photocathode **laser** defines **time structure** of electron beam
- Length of **RF** pulse defines **maximum length** of radiation pulse

- **Repetition rate of RF** defines repetition of **radiation pulse + ** total **irradiation time** during session

This results in very different

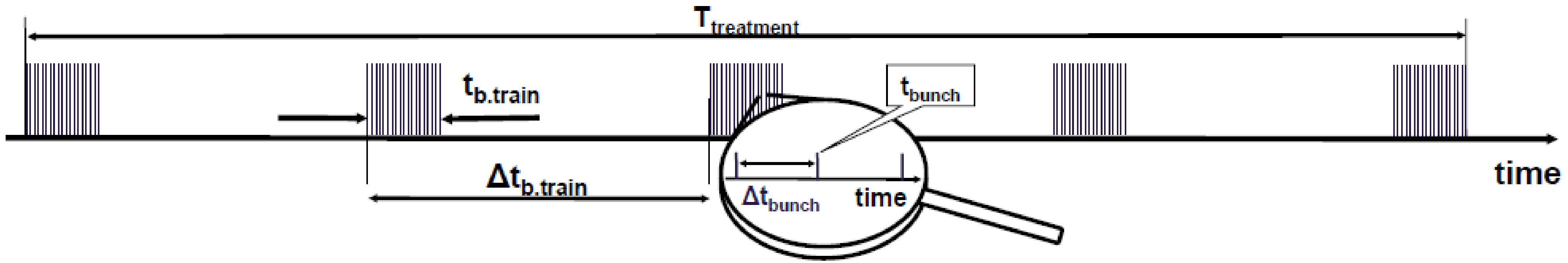
- time structure of radiation pattern
- possibilities to change the time structure flexible

} ➔ experimentally study very different time scales in RT

- bunch charge ➔ instantaneous dose and dose rate
- beam quality ➔ capability to focus beam for mico beam RT + scanning

Definition of relevant beam parameters

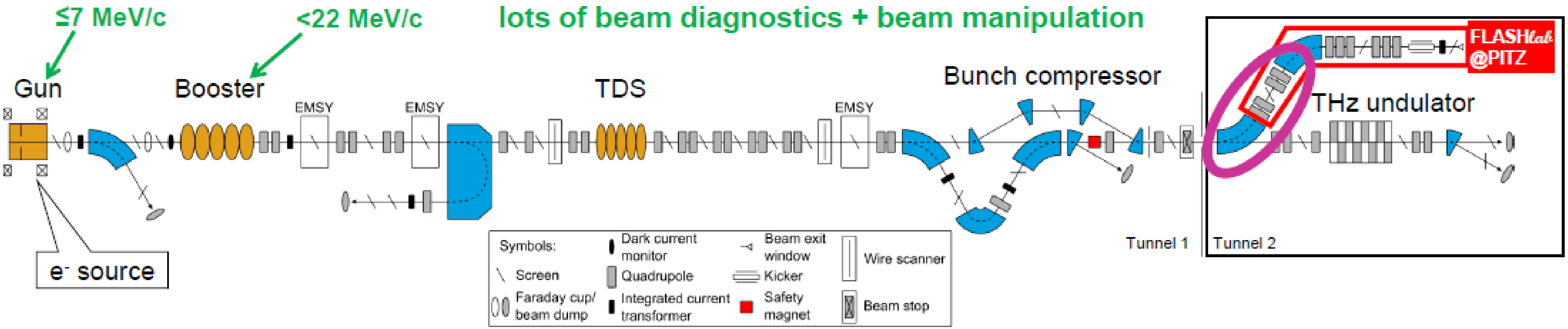
Here: concentrate on timing parameters for one application period (treatment session / positioning of patient)



quantity	description	mainly used till now 3 GHz linac, therm. emission	e.g. PITZ 1.3 GHz linac, photo emission
$T_{treatment}$	Time needed for one treatment session	< 200 ms for FLASH	< 1 ms possible
$t_{b.train}$	Length of **bunch train** (in RT commonly called **'pulse'**)	e.g. 0.5 – 4 µs	0 – 1 ms
$\#_{bunch}$	Number of bunches in bunch train	e.g. 1500 – 12000	1 – 4500
$\Delta t_{b.train}$	Separation of 2 neighboring bunch trains	e.g. 0.003 – 0.1 s	0.1 – 1 s
Δt_{bunch}	Separation of 2 neighboring bunches	0.3 ns	0.2 – 10 µs
t_{bunch}	Length of individual electron bunch, FWHM	e.g. ~30 ps	0.1 – 60 ps
q_{bunch}	Charge per bunch = average current in train * $t_{b.train}$ / $\#_{bunch}$	e.g. 0.1 – 100 pC	0.1 – 5000 pC

Status of realizing FLASHlab@PITZ

B) Start-up beamline for FLASHlab@PITZ → first experiments are done



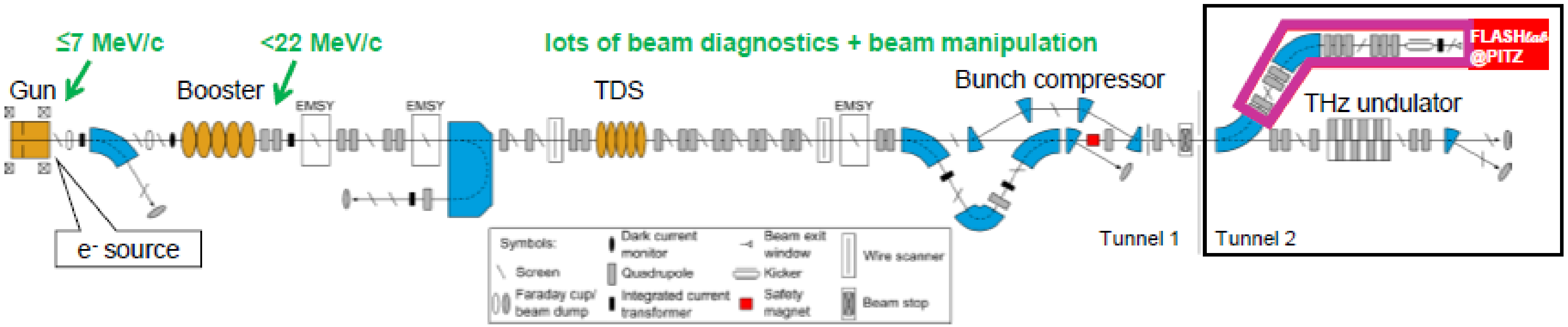
Start-up beamline for FLASHlab@PITZ:

- Allows early experiments on FLASH RT R&D
  - Beam characterization
  - Dosimetry
  - First experiments with chemical, biochemical and biological samples
- Dispersion limits minimum horizontal beam size, only vertical kicker installed

Status of realizing FLASHlab@PITZ

Courtesy of Xiangkun Li

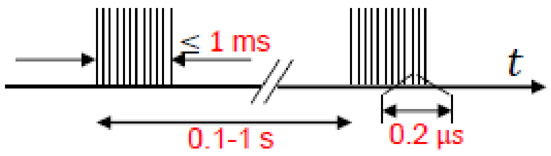
C) Design update of full beamline FLASHlab@PITZ + laser system upgrade

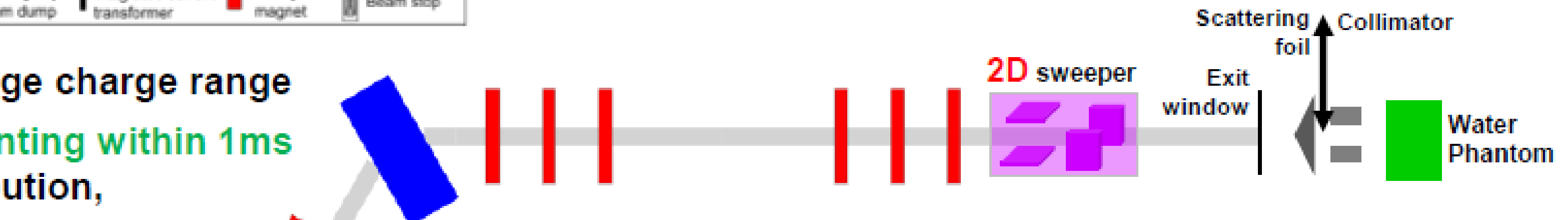


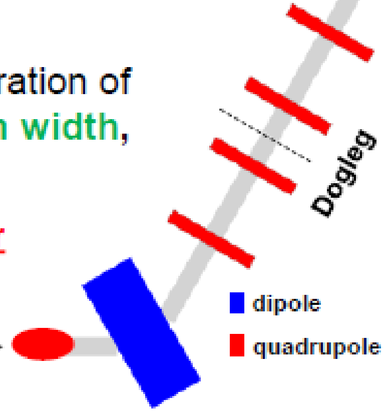
- new photo cathode laser system to be installed in 2023

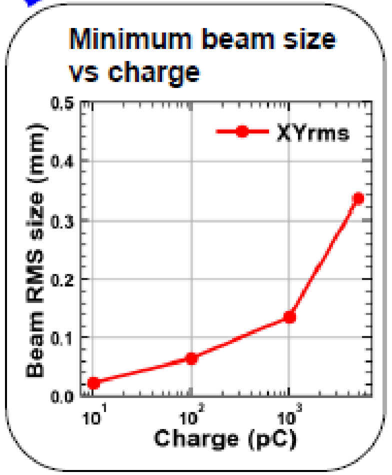
→ even tighter beam control
+ higher flexibility

- **Tiny beam size** reachable in **huge charge range**
- **Sweeper system** allows **2D painting within 1ms**
  → **arbitrary transverse distribution,** no loss from flattening
- **Scattering system** allows generation of **symmetric beam of several cm width**, ~50 % loss due to flattening



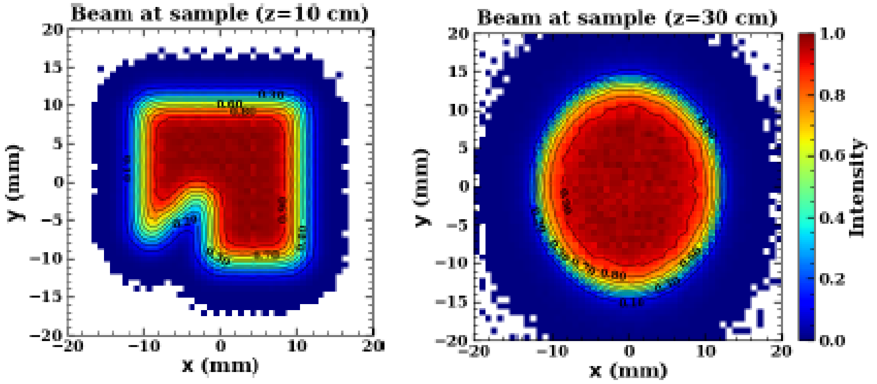






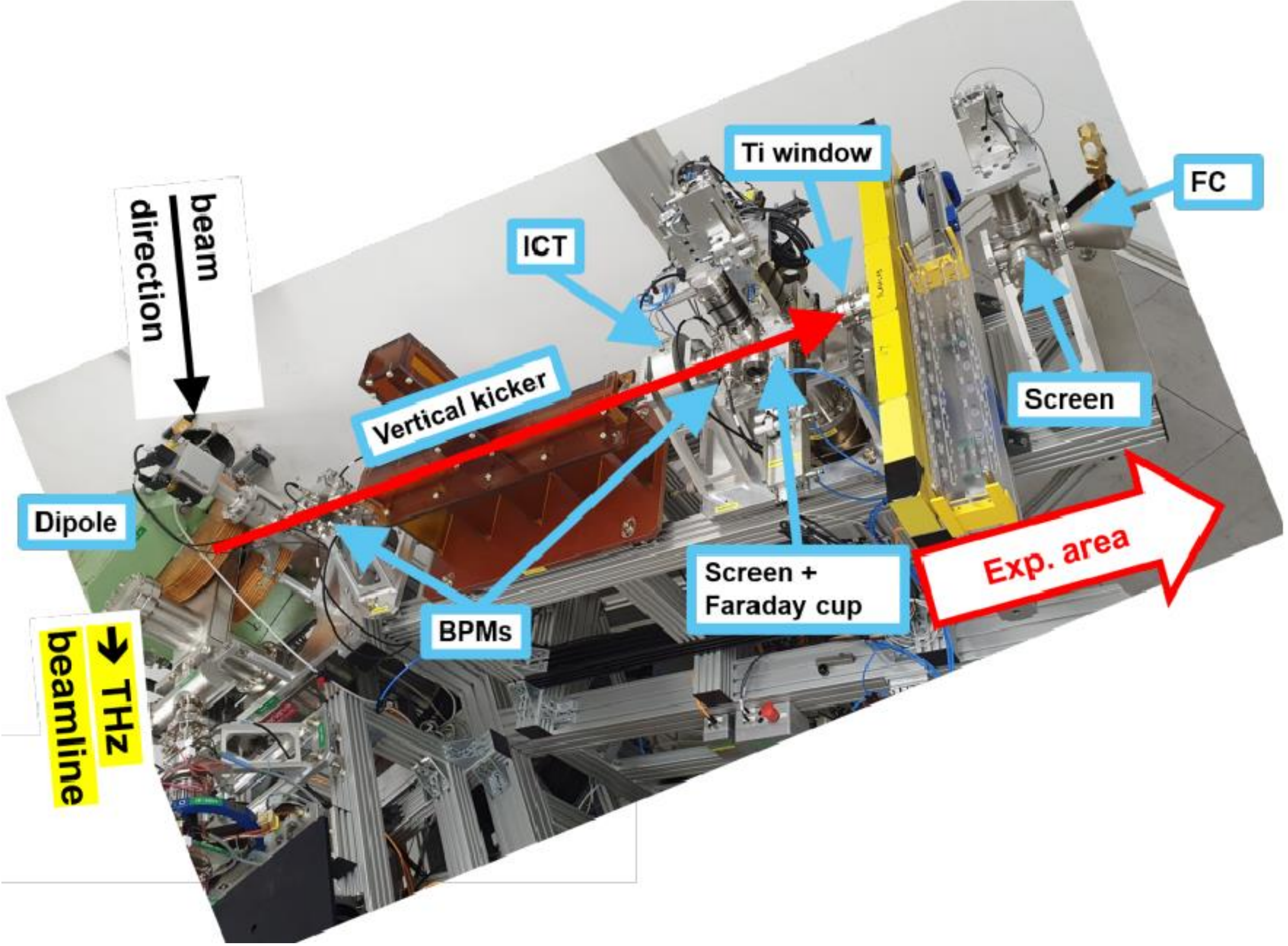
Example beams (the beam field size is easy scalable):

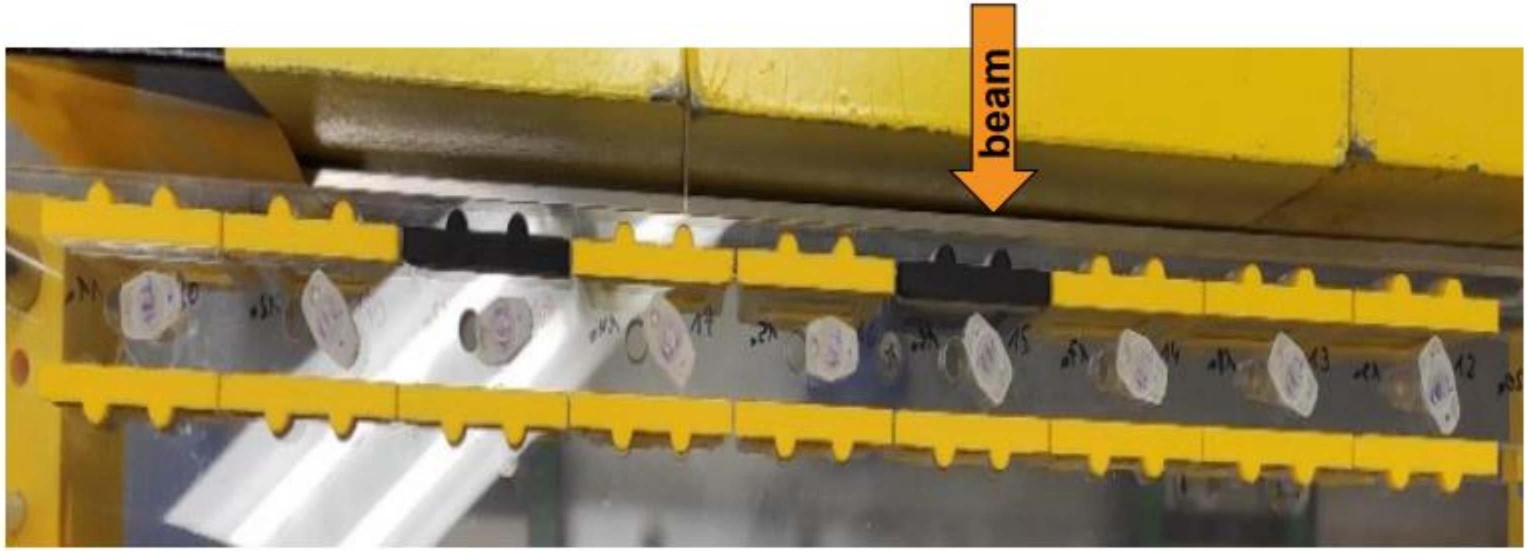
a) From 2D sweeper b) from scattering foil



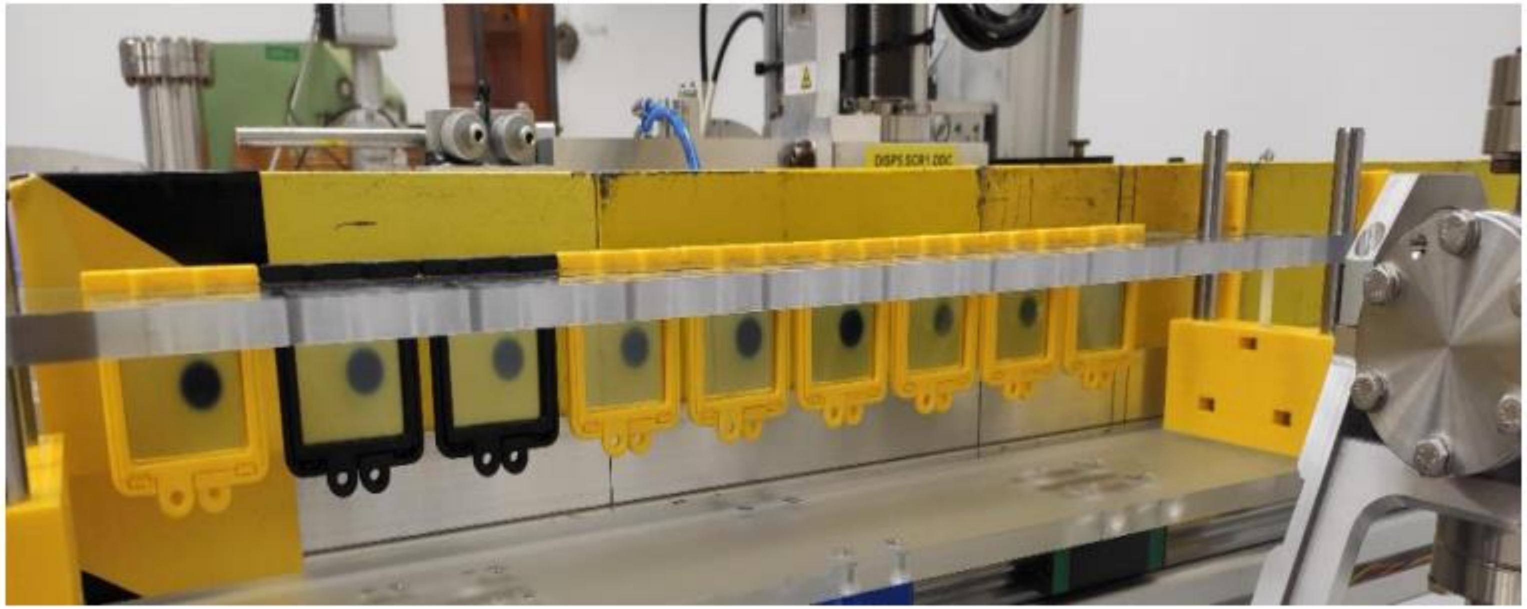
DESY. | Frank Stephan | Progress on FLASHlab@PITZ | FRPT 30.11.2022

First radiation experiments at PITZ





Preliminary setup of FLASH*lab*@PITZ

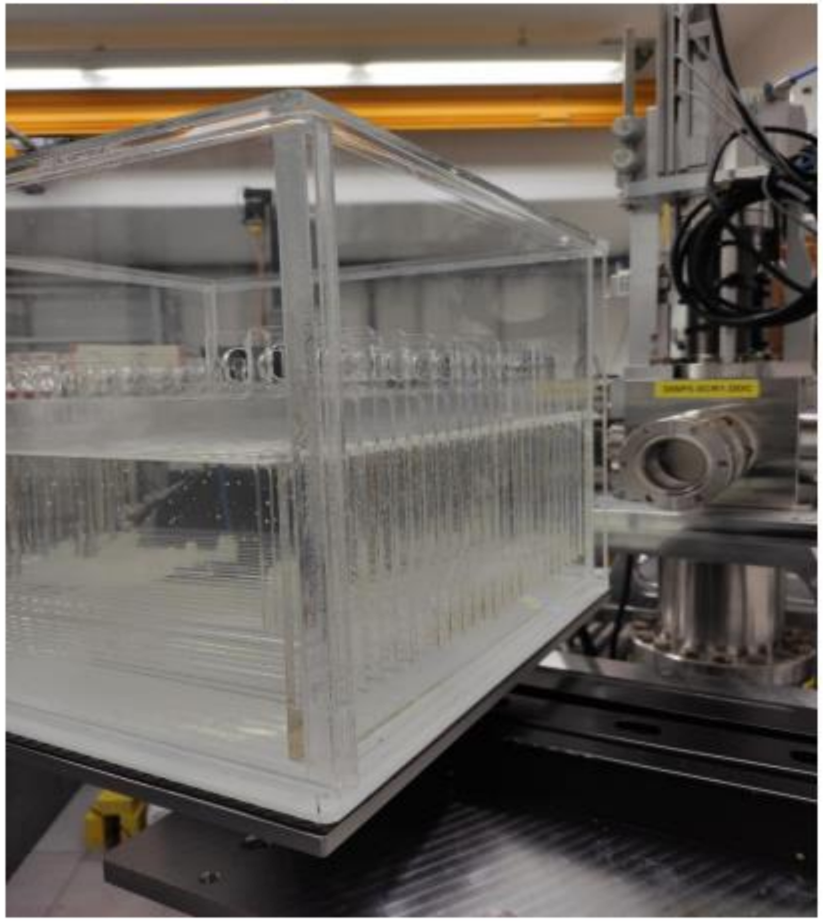


TH WILDAU

MANCHESTER 1824
The University of Manchester

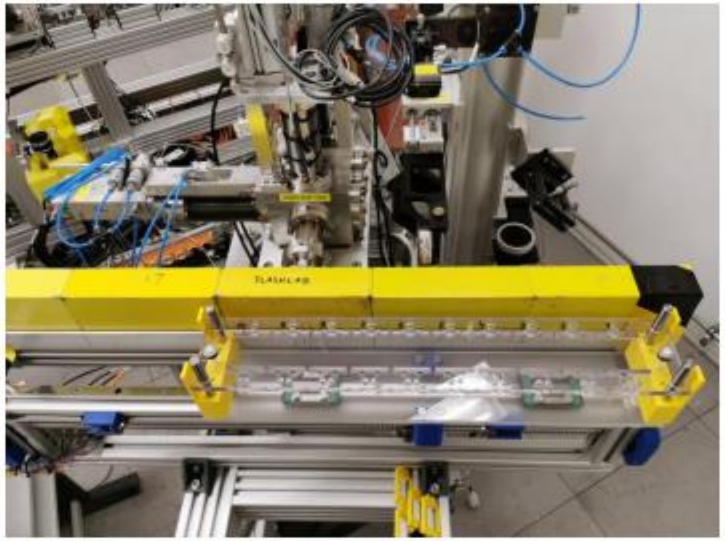
UKRI Science and Technology Facilities Council

PITZ Photo Injector Test Facility Zeuthen



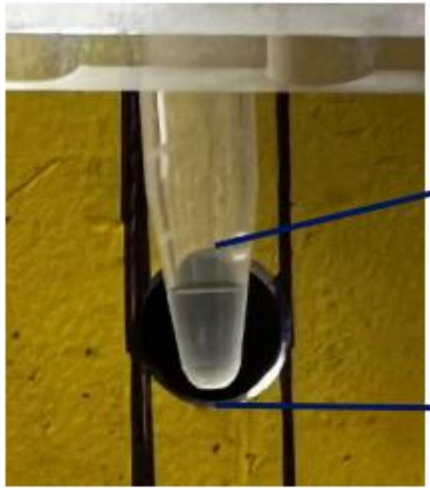
Start-up setup for radiation beamline

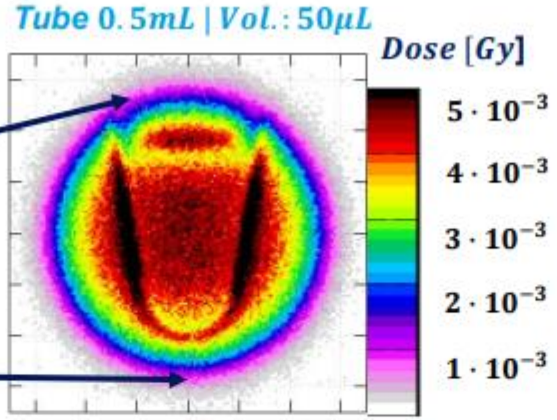
Sample in holder on motorized transverse stage



Courtesy of Frank Stephan

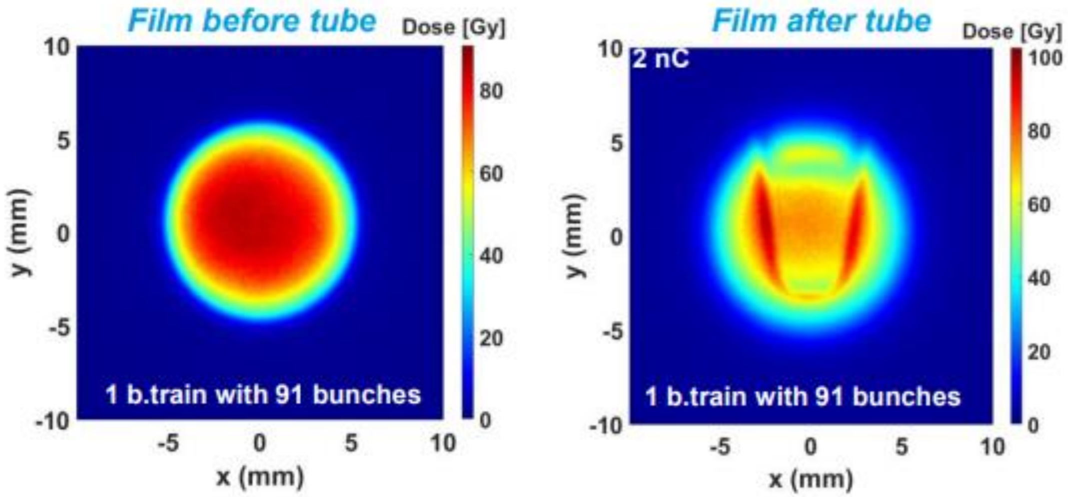
Dose simulation





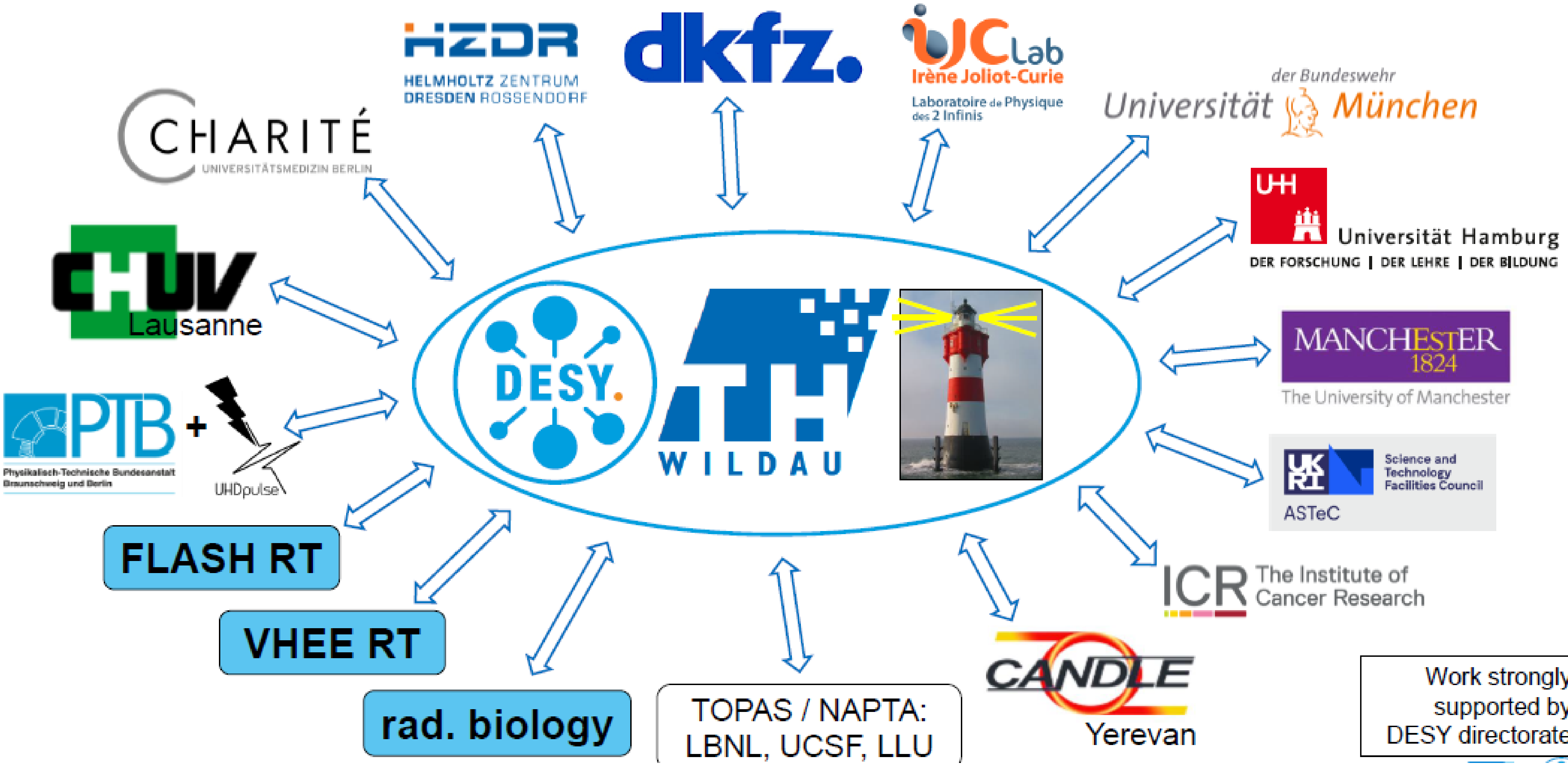
Courtesy of Zohrab Amirkhanyan

Dose measurement with gafchromic films



Courtesy of Felix Riemer

Current cooperation partners of FLASHlab@PITZ :



Work strongly supported by DESY directorate

Summary

- History
- Motivation
- Emittance
- Facility Overview
- Conditioning
- THz FEL at PITZ
- FLASHLab at PITZ

Thank you

Contact

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