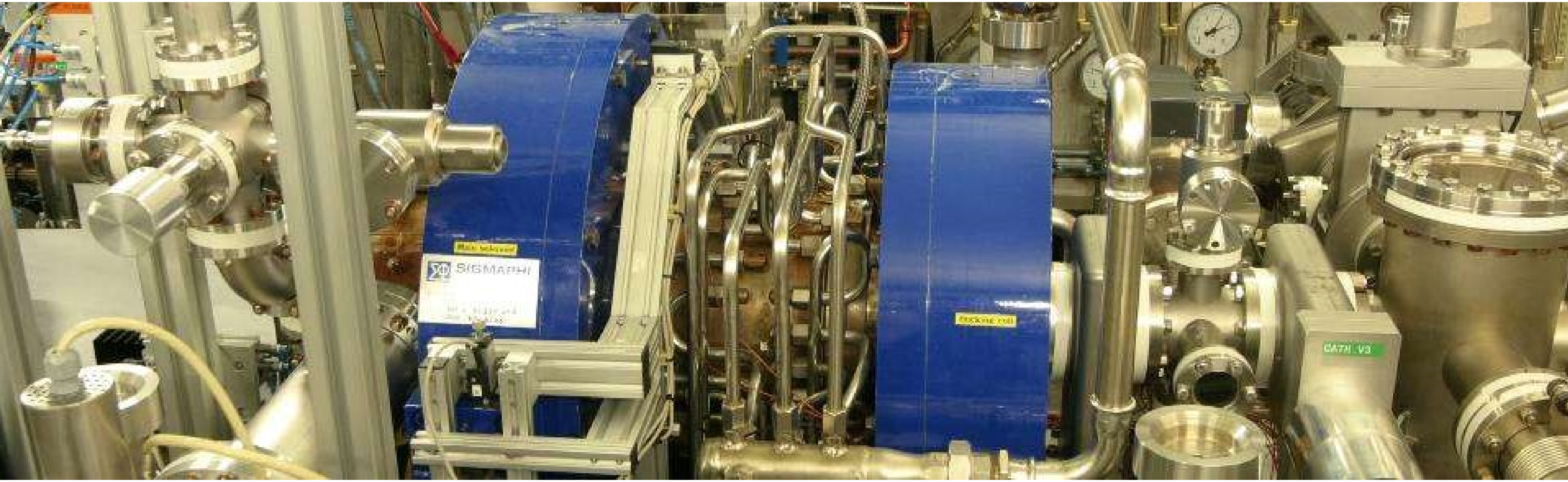


The photoinjector test facility

Accelerator R&D and applications

Anne Oppelt
Summer Student Lecture 2024

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

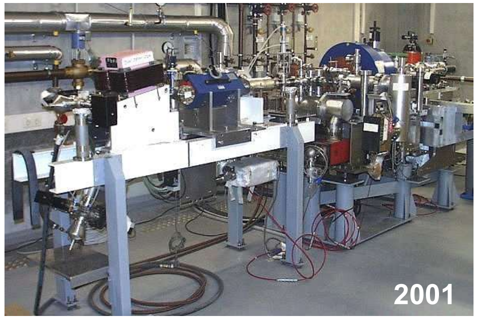
PITZ Photo Injector Test Facility Zeuthen

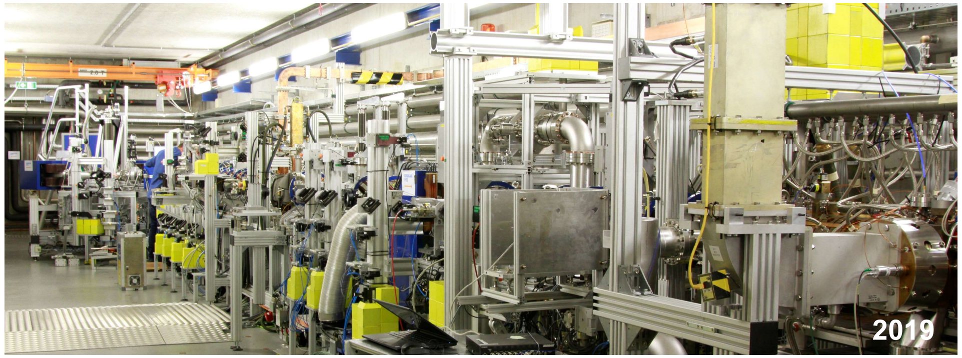
DESY.

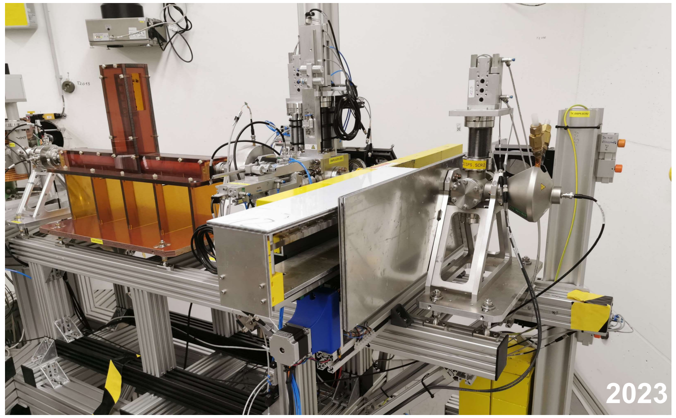
Photo Injector Test facility in Zeuthen

PITZ 1999-2024

- **Original purpose:** development, optimization and delivery of electron sources for user facilities at DESY in Hamburg (FLASH and European XFEL)
- PITZ has been extended several times and developed into much more than a test stand for electron sources
- **Applications** of high brightness electron beams, e.g.
  - Proof-of-principle THz SASE FEL at PITZ
  - Radiation biology studies with FLASH*lab*@PITZ



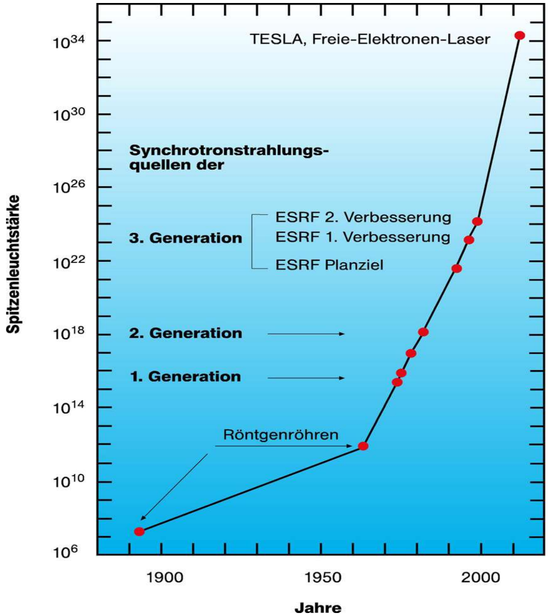


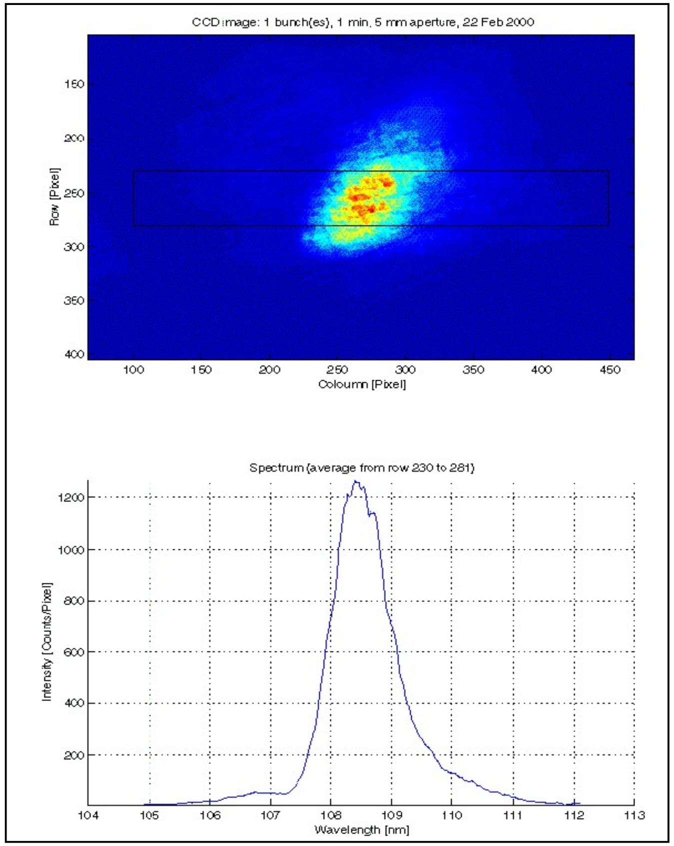


Why PITZ in Zeuthen?

- Development of a photo injector for high quality electron beams as driver of a Free Electron Laser (FEL)
  - 1997: Conceptual Design Report of a 500 GeV e+e- Linear Collider with Integrated X-ray Laser Facility (TESLA)
  - 1999: Decision to build PITZ as a user-independent test facility
  - 2000: TTF1 demonstrates SASE-Prozess (precondition for SASE FEL)
  - improvement of the electron beam quality (brightness) required

Undulator structure



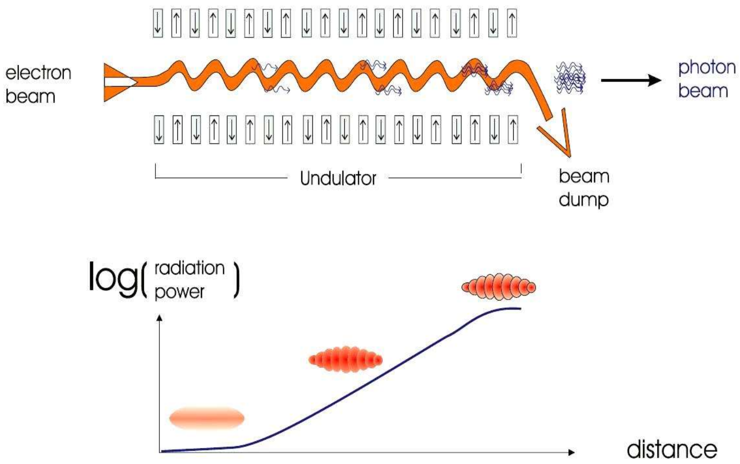


First SASE light at TTF1 in 2000

Free Electron Laser (FEL)

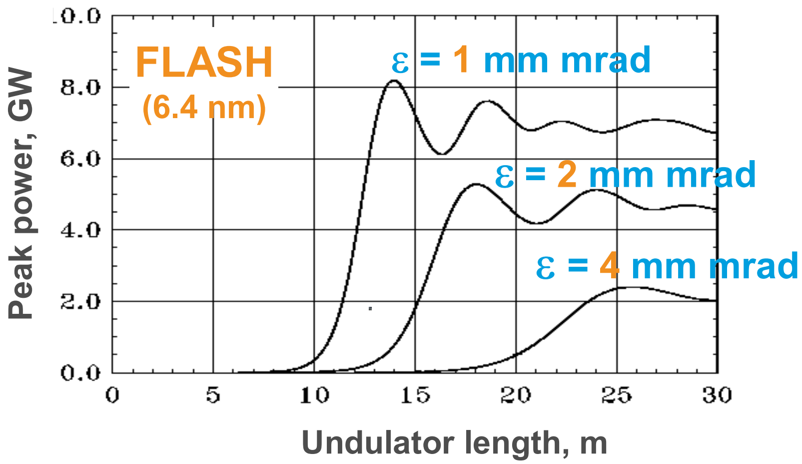
- principle of SASE (Self-Amplified Spontaneous Emission)
  - electrons oscillate in a periodic magnetic field (undulator) and produce high energetic bremsstrahlung → **X-ray** photons of **very small bandwidth**
  - interaction of electrons and photons generates micro bunching (slicing) → **very short photon pulses**
  - coherent radiation of all electrons in a slice leads to a self-amplification of the radiation (SASE) → **very high intensity**
- high brightness electron beams are precondition to trigger SASE
  - small transverse emittance (spot size, angular divergence)
  - small longitudinal emittance (bunch length, energy spread)

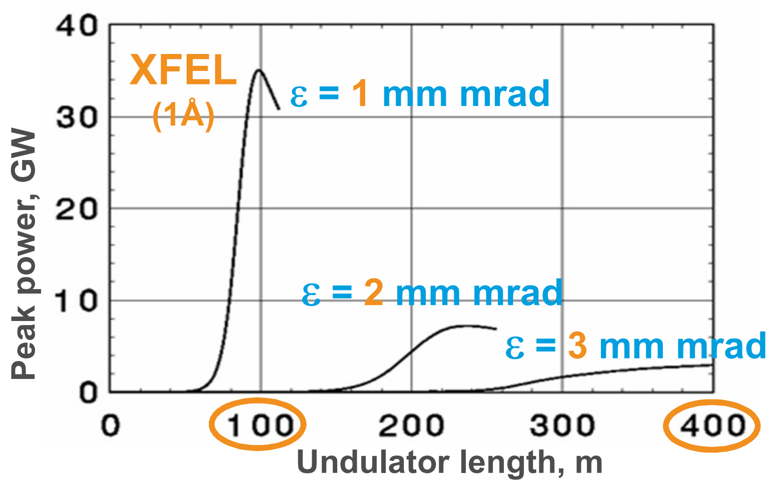
Goal emittance for the XFEL:
0.9 mm mrad @ injector, i.e.
1.4 mm mrad @ undulator entrance



Free Electron Laser in the Self Amplified Spontaneous Emission (SASE) mode

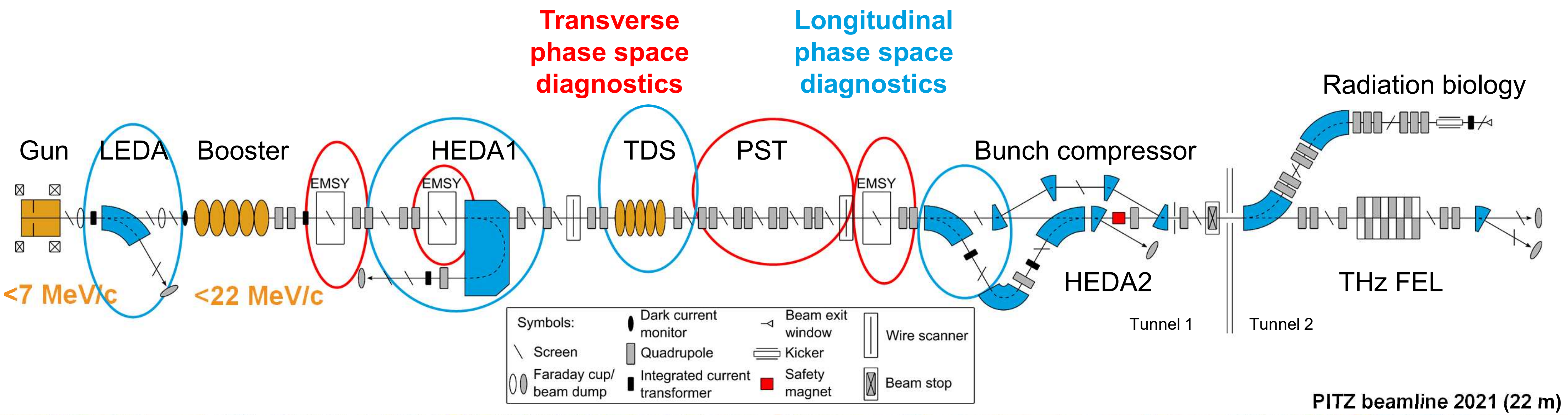
Image: TESLA Technical Design Report Part I



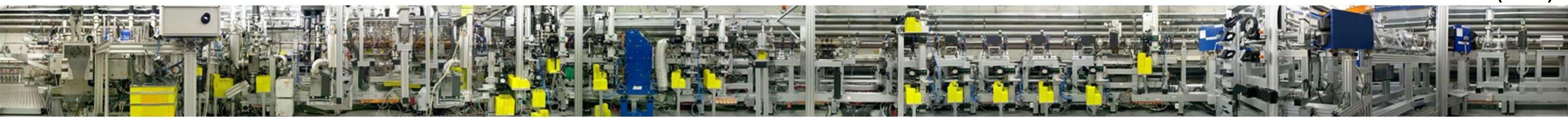


Facility overview

- normal conducting 1.3 GHz RF gun and booster
- lots of beam diagnostics + beam manipulation capabilities
- continuous improvements of all **subsystems** to optimize beam quality and stability

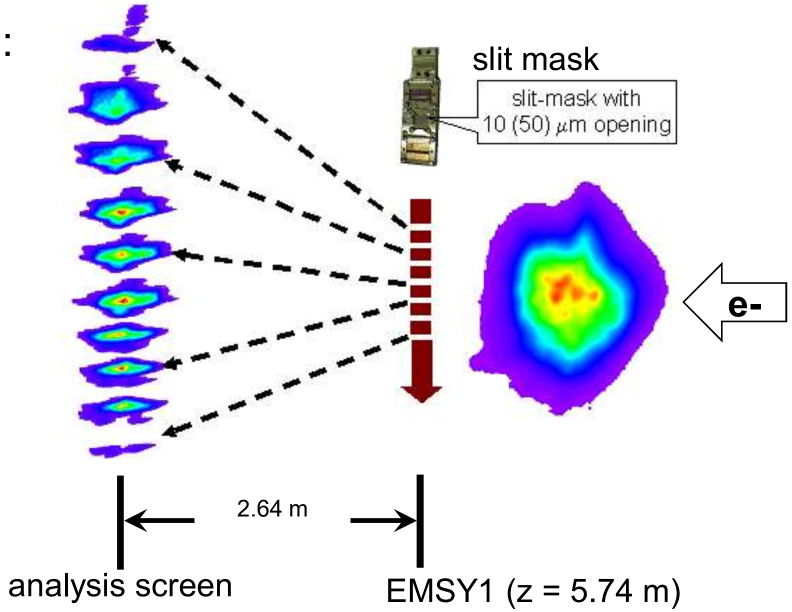


PITZ beamline 2021 (22 m)



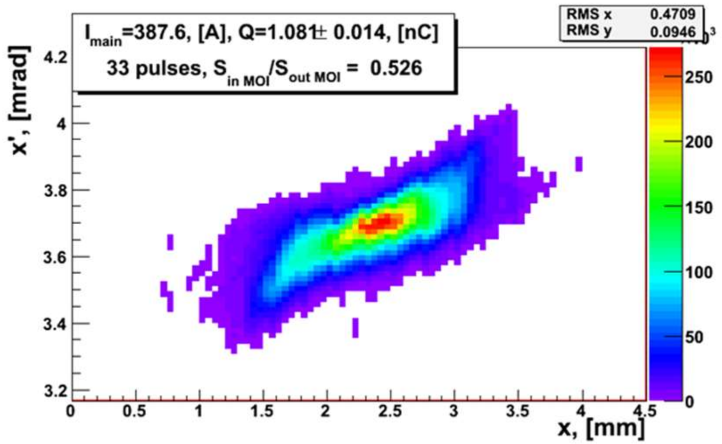
Transverse emittance measurements

- Beam emittance measurements are done using the slit mask technique:
  - beam **size** at YAG screen at the positions of the slit mask
  - insert slit mask to cut the beam in space charge free, emittance dominated **beamlets**
  - observe beamlets at an observation screen after a drift to measure the beam **divergence**
  - **scale** the obtained **100% emittance**



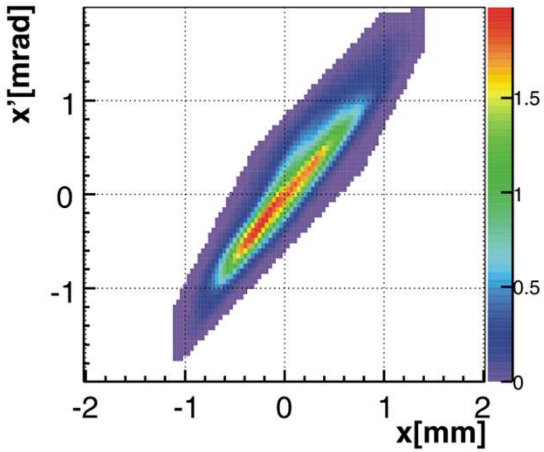
$$\varepsilon_n = \frac{\sigma_x}{\sqrt{\langle x^2 \rangle}} \beta\gamma \sqrt{\langle x^2 \rangle \cdot \langle x'^2 \rangle - \langle x x' \rangle^2}$$

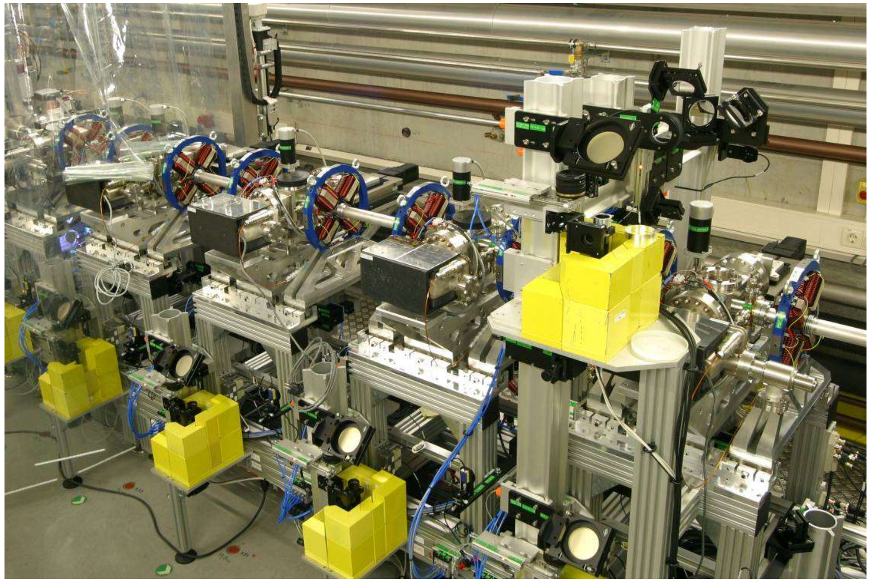
account for underestimation of beamlet size due to weakness of beamlets

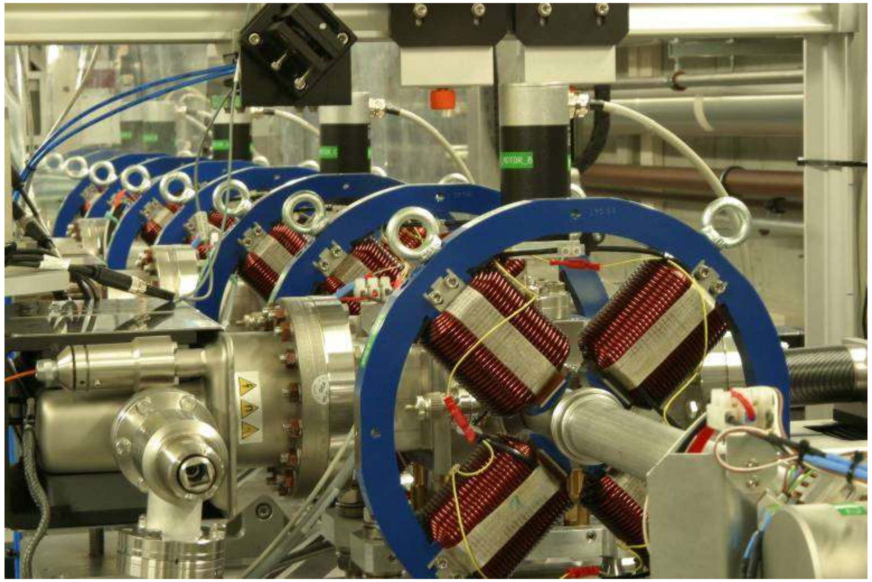


Phase space tomography

- Tomography module:
  - periodic arrangement of quadrupole magnets and screen stations for phase space measurements
  - using a tomographic algorithm, the phase space can be reconstructed in a single-shot measurement
  - Problem at PITZ: space charge influence cannot be neglected

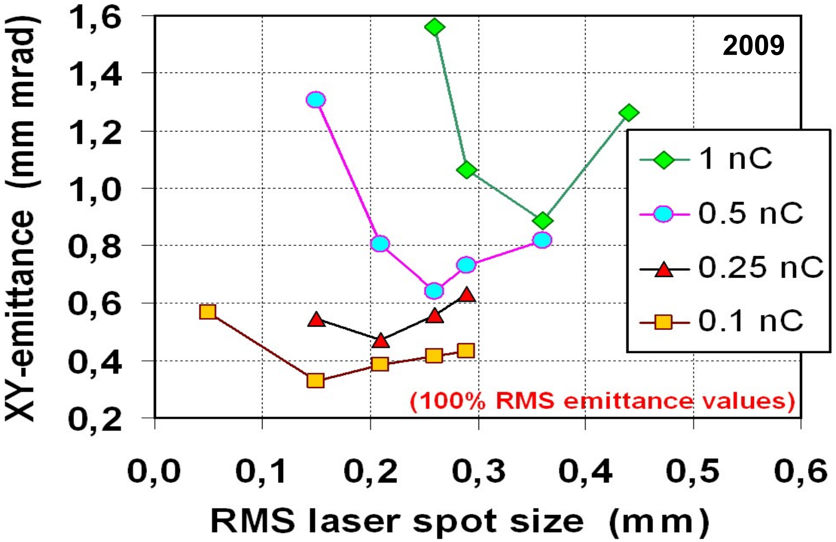




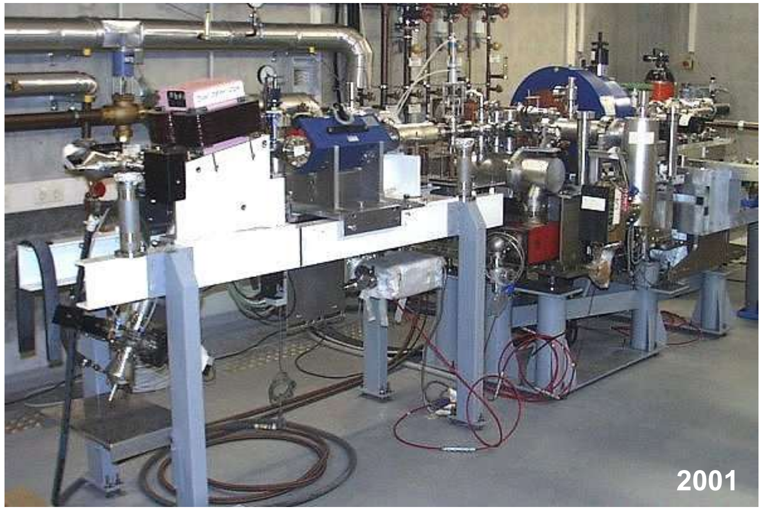


Characterization of high brightness electron beams

- 2001: PITZ is set into operation with the original purpose of development, optimization and delivery of electron sources
  - first photo electrons at PITZ in January 2002
  - delivery of the first optimized electron source to TTF2 (FLASH) in 2003
  - beam parameters required for the operation of an X-ray FEL are reached for the first time in 2007
  - continuous improvements of all **subsystems** to optimize beam quality and stability



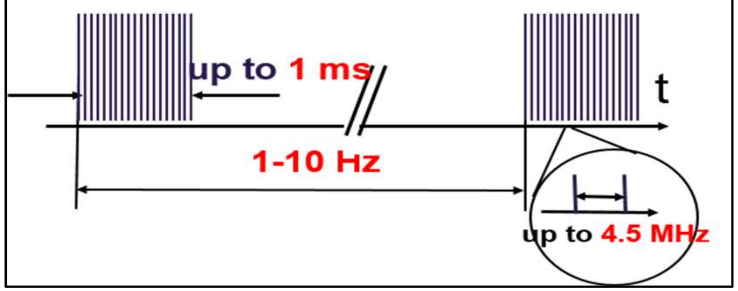
S. Rimjaem et al. NIM A 671 (2012) 62-75



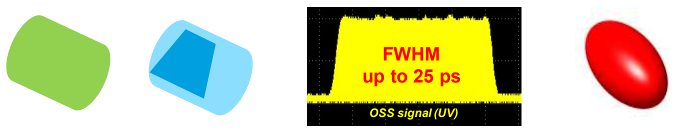
Optimization of high brightness electron beams

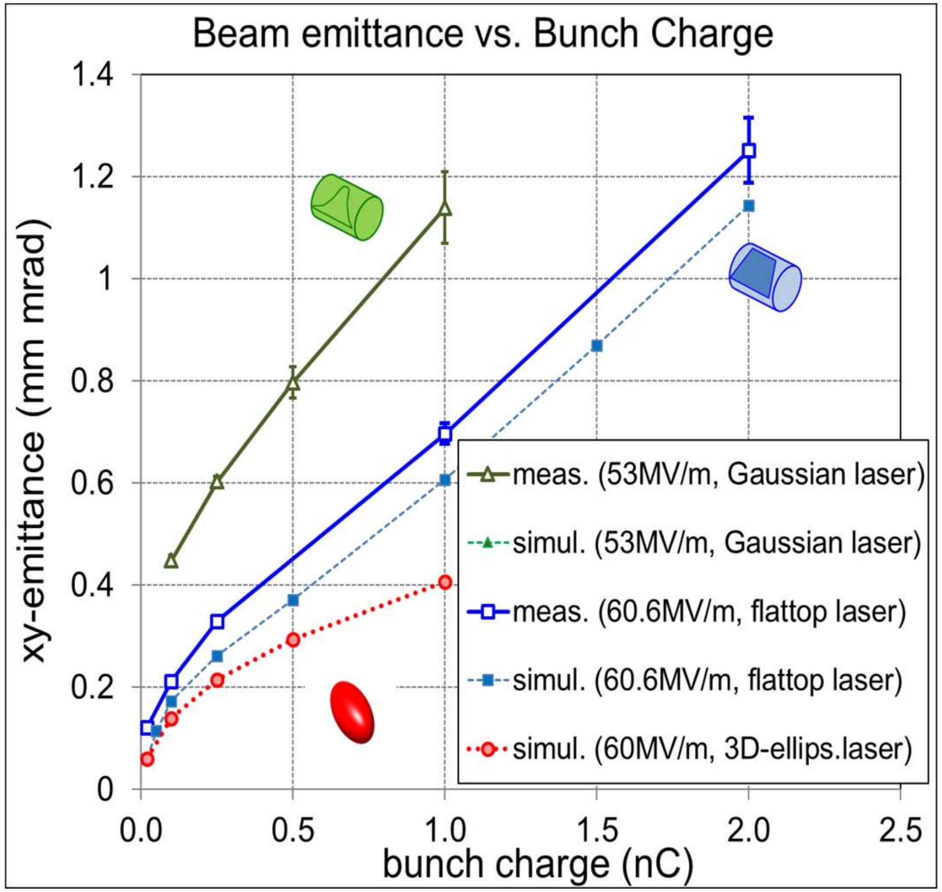
- the photocathode laser is one of the crucial subsystems
  - pulse train structure with up to 27000 buches per second
  - photocathode laser system (λ=257nm) with advanced temporal (micro) pulse shaping
  - emittance optimization towards best beam quality

Pulse Train Time Structure:



Laser pulse shapes:



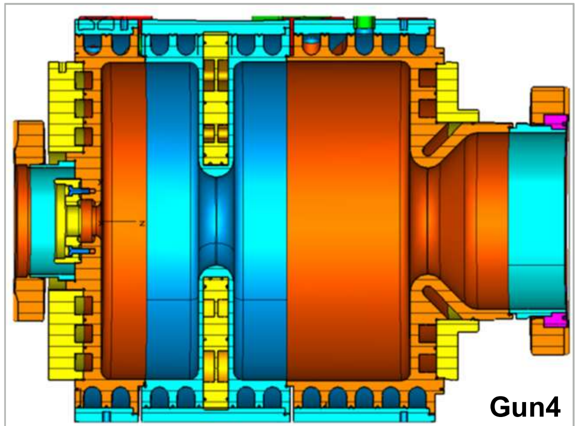


Courtesy: M.Krasilnikov

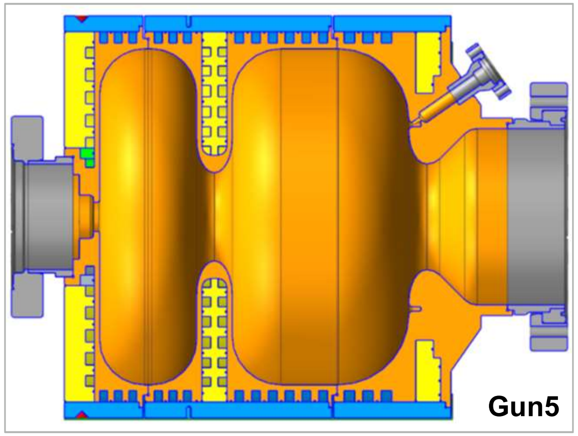
M. Krasilnikov et al., PRST-AB 15, 1000701 (2012).

Gun development for FLASH and European XFEL

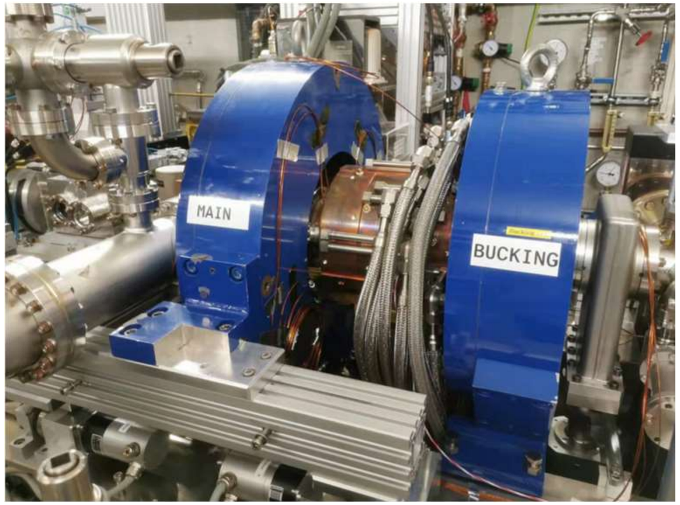
- In total, 10 different electron sources (guns) have passed through the PITZ facility
  - over the years, 5 optimized gun setups have been delivered to FLASH, and 3 to EuXFEL
- Gun5 is the latest generation of cavities, with improved cell geometry (elliptic iris), optimized water cooling for 1 ms RF pulse duration, and RF pickup(s) for better LLRF regulation
  - Gun5.1 is in operation at PITZ
  - Gun5.2 is being commissioned at FALCO, the new conditioning teststand in Hamburg
  - 4 further guns of the same type are under production
  - after their preparation at PITZ, the new guns are foreseen to be used at FLASH and EuXFEL (from 2025+)



Gun4



Gun5



Gun5.1

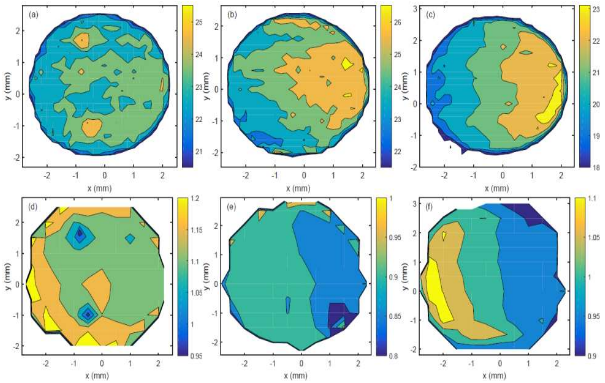
Photo cathode developments

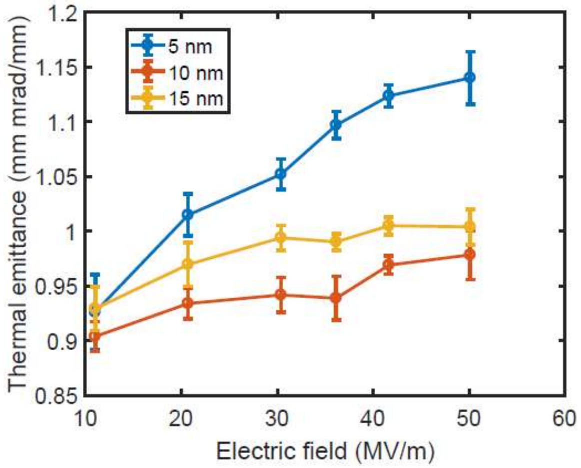
- to date **Cs_2Te cathodes** used; **UV laser** system (λ=257nm) required
  - **Advantages**: low dark current, high life time + robustness
  - standard production for DESY's facilities (EuXFEL, FLASH, PITZ) is done at DESY in Hamburg
  - special cathodes for R&D studies are developed by INFN LASA Milano

5 nm | 10 nm | 15 nm

QE map

thermal emittance map



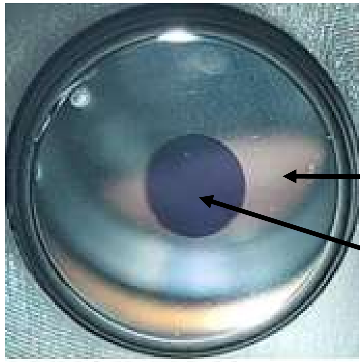


Example: Cs_2Te cathodes with different Te thicknesses were tested

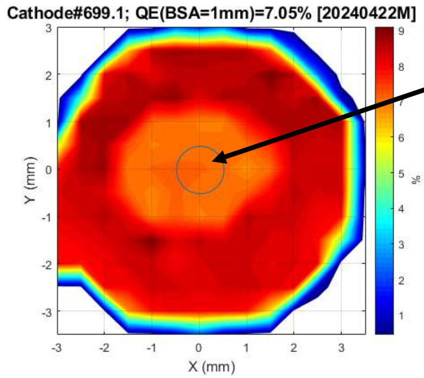
=> anti-correlation between QE and thermal emittance observed

Courtesy: F.Stephan

Peng-Wei Huang, Houjun QianPRAB 25, 053401 (2022)



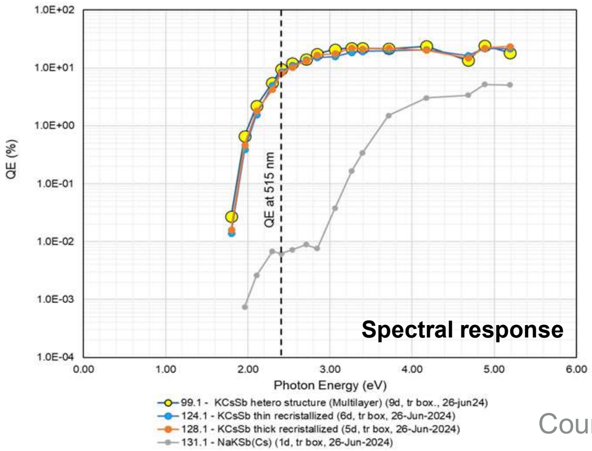
Front view of a photo cathode



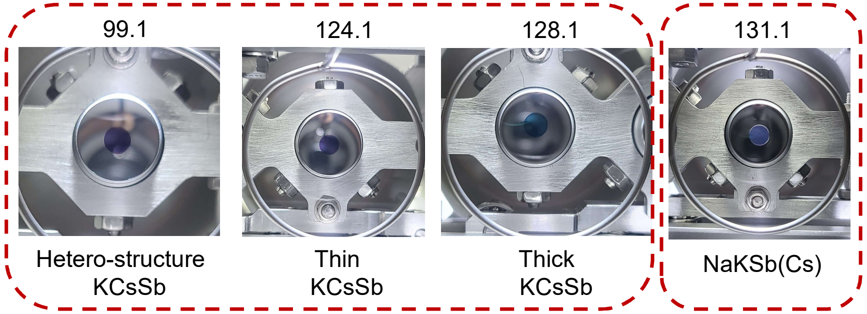
QE map of a used Cs_2Te cathode

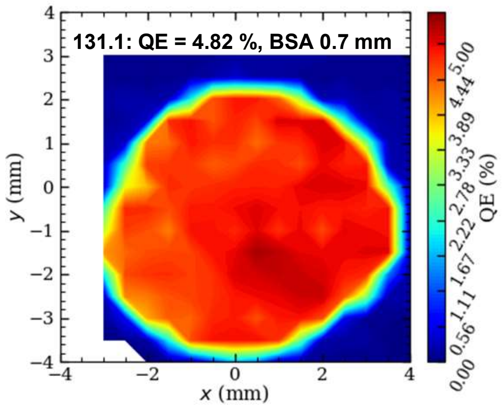
Photo cathode developments

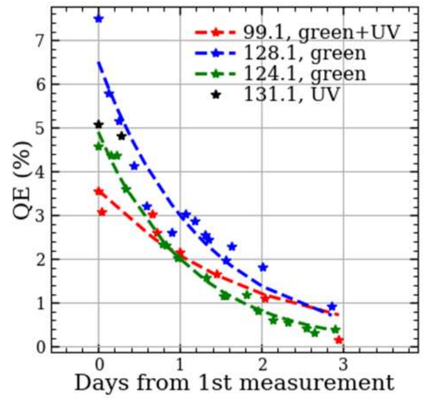
- Development of **„green“ cathodes** in the framework of a PhD thesis
  - **Advantages:** lower thermal emittance and simplified photo cathode **laser system** by omitting conversion to the UV (reduced losses / reduced laser power requirements, less degradation of laser pulse shaping / better laser stability)
  - different new materials are being investigated, e.g. KCsSb and NaKSb(Cs)
  - cathode development is done at INFN-LASA Milano; cathode tests at PITZ
  - **Results of the first tests:** thermal emittance reduced, but QE and lifetime issues → improvements and further optimization of the cathode recipe
  - recipe was further developed and 3 different KCsSb cathodes and 1 NaKSb(Cs) cathode have been produced with sequential deposition in June 2024 and tested at PITZ in July 2024
- Further planned investigations
  - cathode degradation studies
  - surface characterization studies
  - …



Courtesy: S.Mohanty

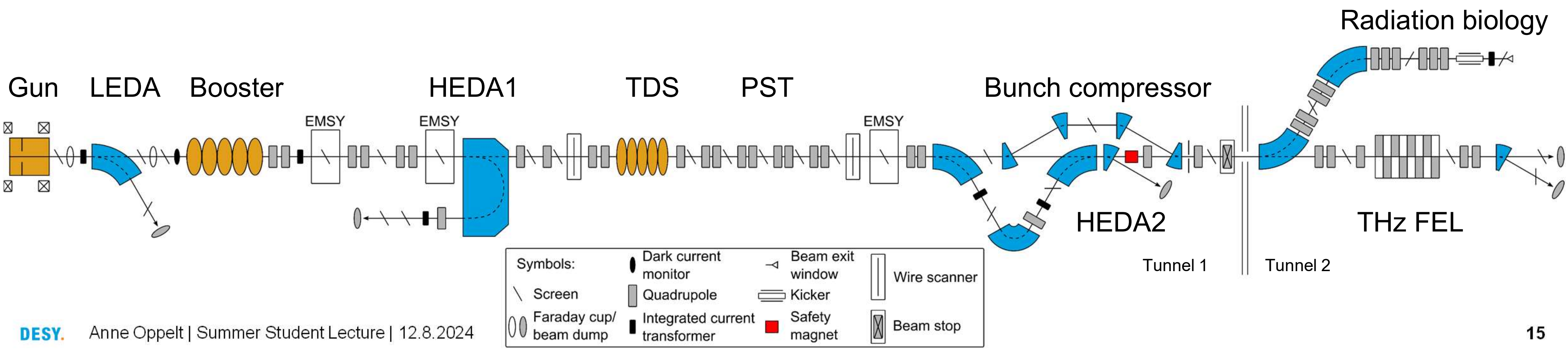




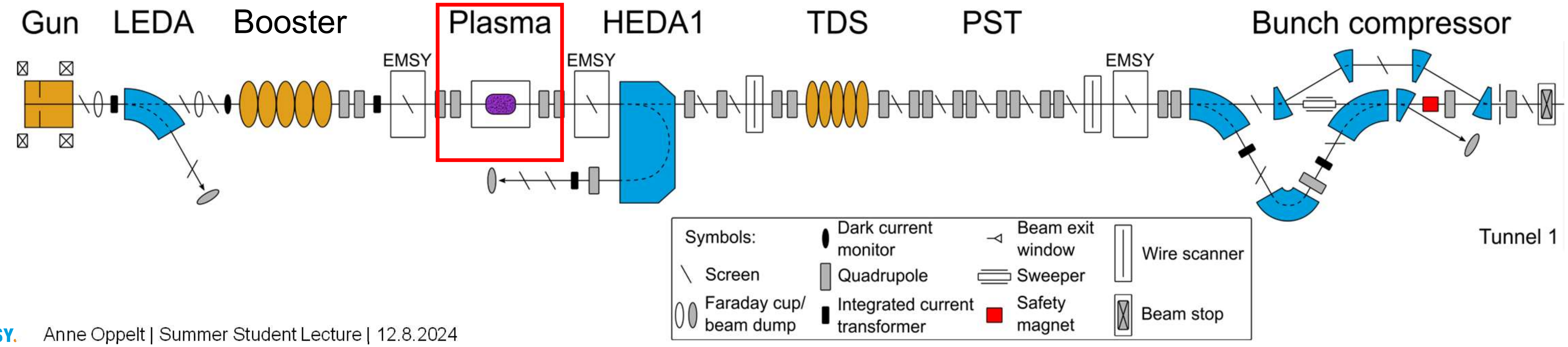


Applications of high brightness electron beams

- PITZ has been extended and developed meanwhile into much more than a test stand for electron sources
- wide application spectrum due to extremely flexible beam parameters
  and a large diversity of beam diagnostics tools
- Examples:
  - R&D on beam driven plasma acceleration
    a) experimentally proving self-modulation instability
    b) high transformer ratio measurements
  - THz SASE FEL
  - FLASH radiation therapy and radiation biology

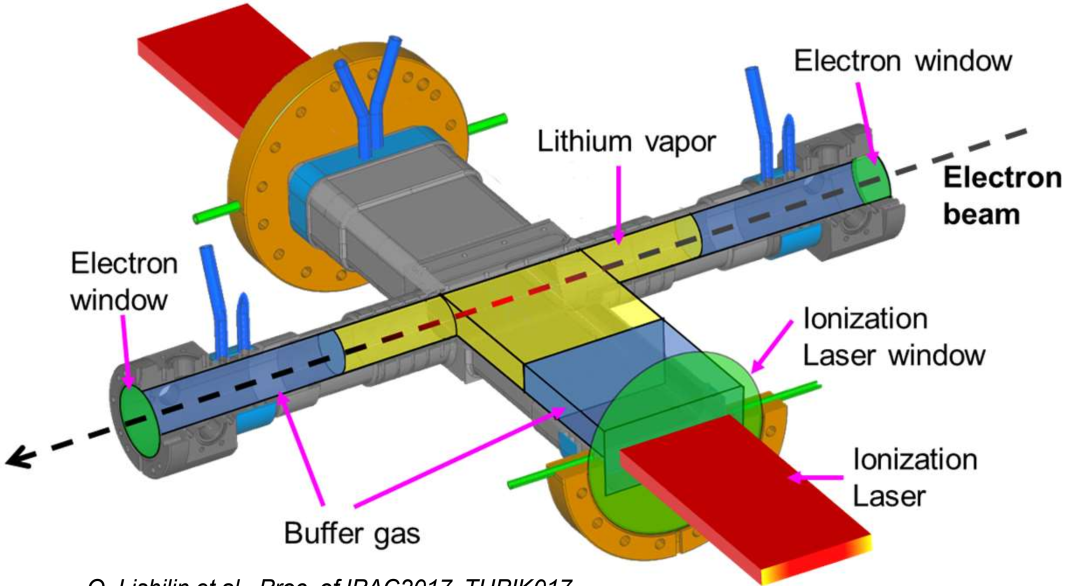


R&D on beam driven plasma acceleration

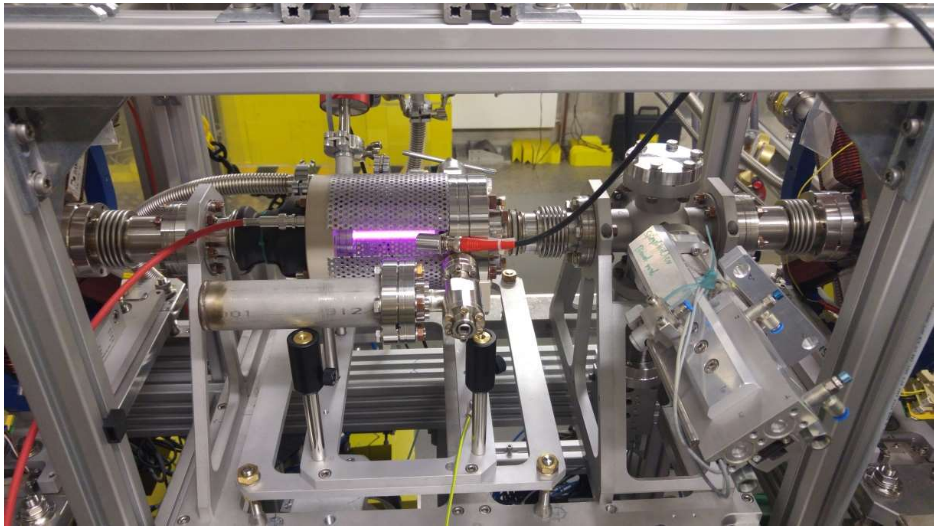


R&D on beam driven plasma acceleration

- two different types of plasma cells have been built and successfully used at PITZ in the framework of PhDs
  - **Lithium plasma cell**: unique plasma cell with sideward coupling windows for the ionisation laser
    Advantages: well defined, adjustable length of the plasma channel; production of different plasma profiles possible
    Disadvantage: technically very challenging
  - **Argon gas discharge plasma cell**: simple principle, easily scalable



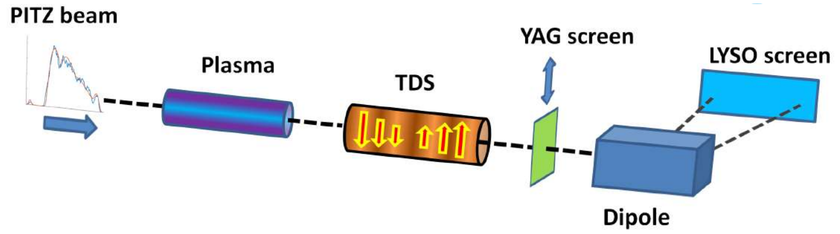
O. Lishilin et al., Proc. of IPAC2017, TUPIK017



G. Loisch et al., J. Appl. Phys. 125, 063301 (2019)

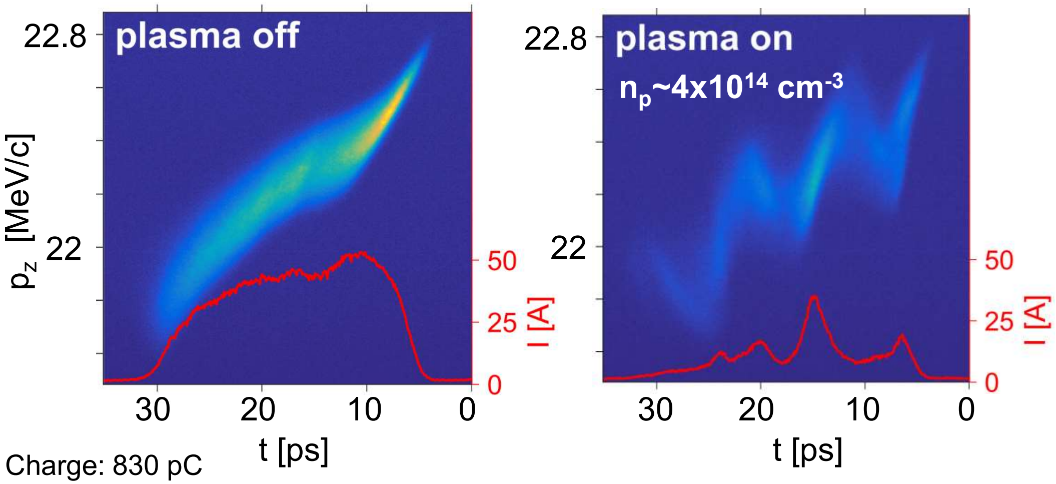
Beam driven PWFA Research at PITZ

… using time resolved electron beam diagnostics



➢ Self Modulation Instability

- **Motivation**: AWAKE experiment at CERN (single stage electron acceleration with self modulated proton beam)
- **Demonstration at PITZ**: characterization of self-modulation with flexible electron beam

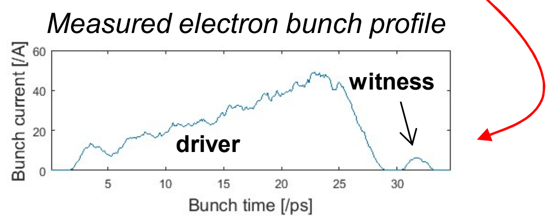


Charge: 830 pC
Plasma density: ≈10^{14} cm^{-3}

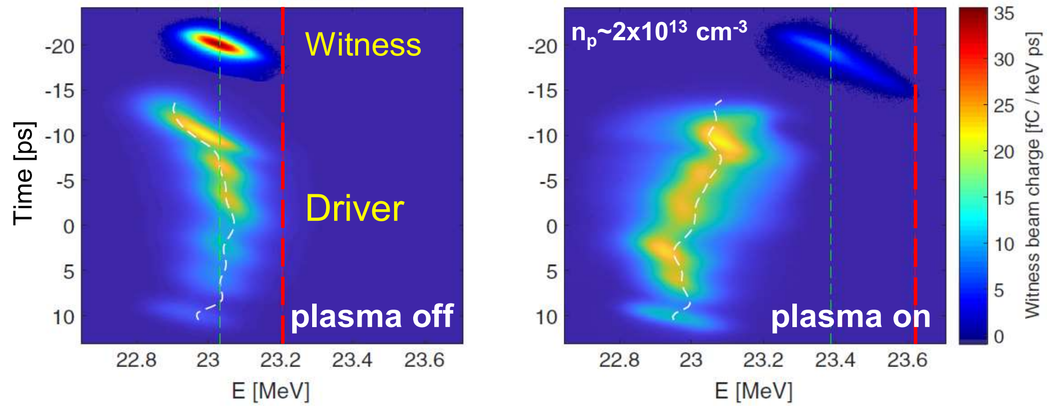
M. Gross et al., Phys. Rev. Lett. ***120****, 144802 (2018)*

➢ High Transformer Ratio

- **Idea**: Increase ratio of witness energy gain to driver energy loss (TR) with asymmetric drivers
- **Demonstration at PITZ**: Time resolved energy measurement (slice energy) by using double triangular driver bunch

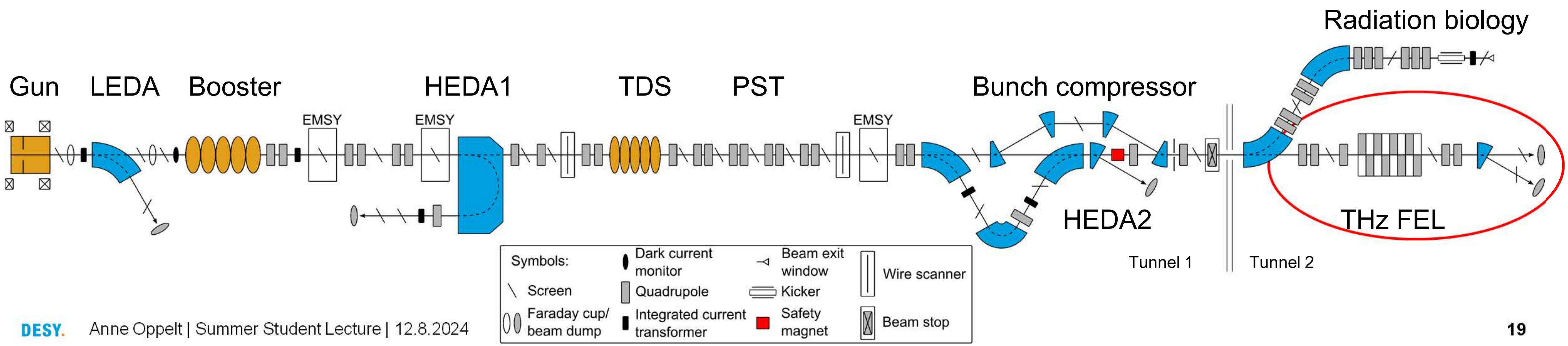


TR = $4.6^{+2.2}_{-0.7}$



G. Loisch et al., Phys. Rev. Lett. ***121****, 064801 (2018)*

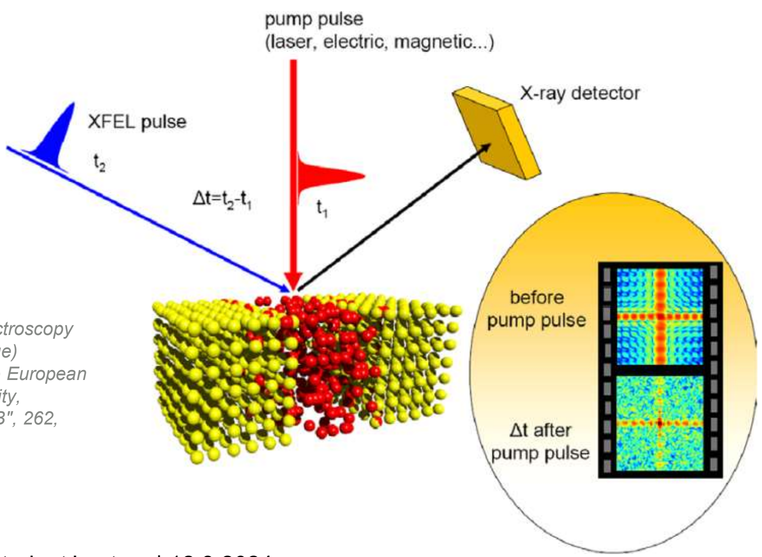
Proof-of-principle THz SASE FEL at PITZ

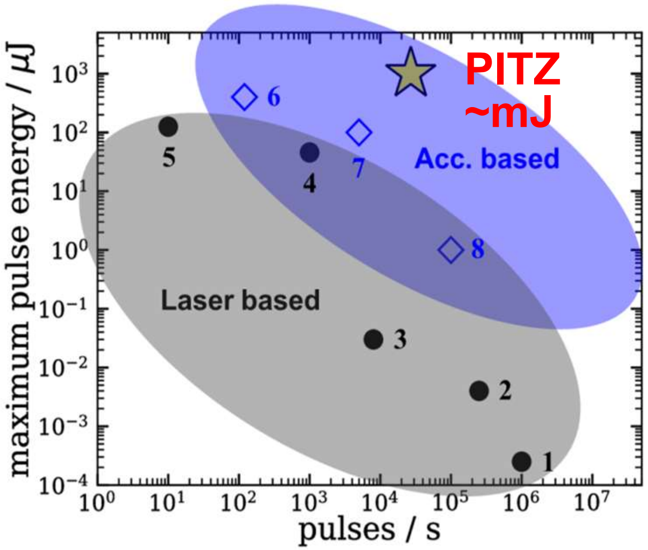


Pump-probe experiments with THz radiation

- EuXFEL users are very interested in THz pump / X-ray probe experiments due to the manyfold applications:
  - Studies of protein **dynamical transitions** and tertiary native proteins with structural motions
  - Characterization of ions and molecules where solvation process plays a relevant role in the **modification of** their **structure and properties**
  - Condensed matter physics: study of **non-linear effects** aiming to the control the state of material which could lead to new applications
  - **Phase change** of materials
  - Highly correlated materials (magnetoresistance, ferro-electrocity, superconductivity, insulator-to-metal transitions, etc)

X-ray photon correlation spectroscopy (XPCS pump–probe technique) G. Grübel et al. "XPCS at the European X-ray free-electron laser facility, Nucl. Instrum. and Methods B", 262, 357-367 (2007).

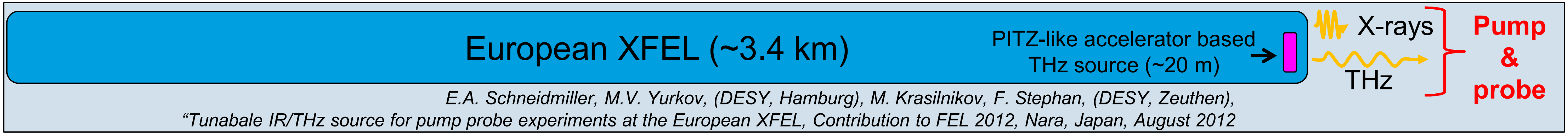




Courtesy: M.Krasilnikov

Prove-of-principle THz SASE FEL at PITZ

- a PITZ-like accelerator allows to produce **mJ-level THz radiation** at the repetition rate of European XFEL

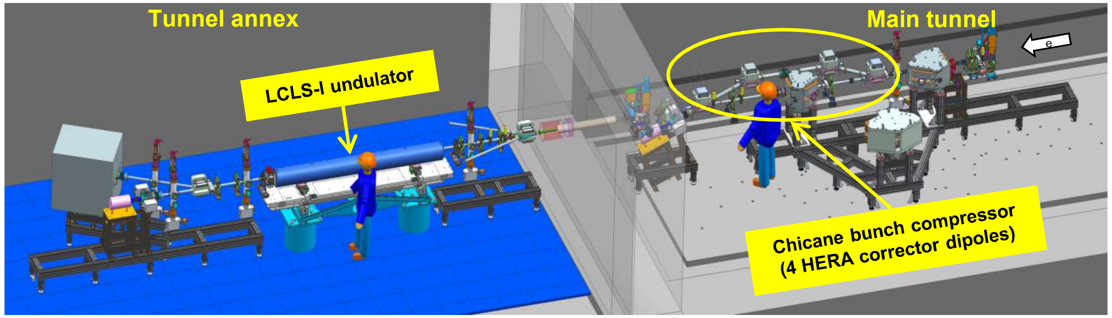


Courtesy: M.Krasilnikov

- **Idea:** built an accelerator-based, high intensity + high repetition rate THz source demonstrator at PITZ
- Proposed R&D Project for European XFEL in 2018: *„Conceptual design of a THz source for pump-probe experiments at the European XFEL based on a PITZ-like photo injector"*
- Project was **approved** and started Q2/2019
- Two main project phases:
  - design and built the facility (tunnel extension)
  - study and improve THz light properties
- **submit** Conceptual Design Report (**CDR**) for an accelerator-based THz source at the European XFEL

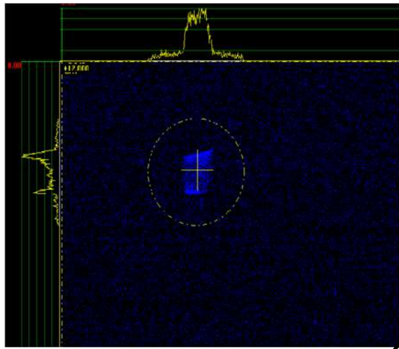
THz SASE FEL: from design to technical installation

- Realization of the THz SASE FEL at PITZ required a lot of installation work in both tunnels:
  - **bunch compressor** in the old accelerator tunnel to increase the electron beam current
  - **undulator and THz diagnostics** in the tunnel extension
  - in total ~100 new components installed



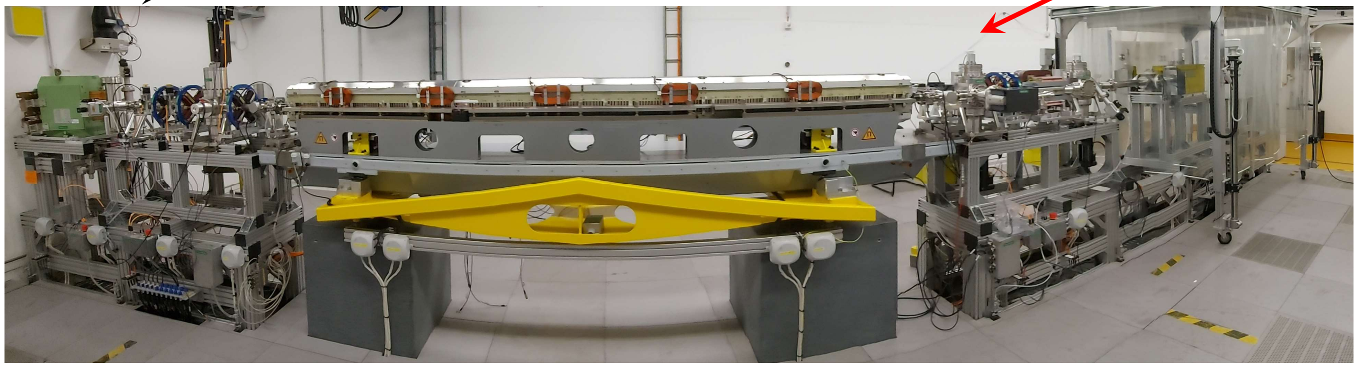
Commissioning of the THz SASE FEL

- installations and commissioning of components was done step by step
- **first beam** downstream the undulator detected on July 22 around 04:30
- **first lasing** on 9.8.2022 (1 nC, 17 MeV/c)
- **inauguration** of the THz FEL with Brandenburg‘s ministry for research on 28.11.2022

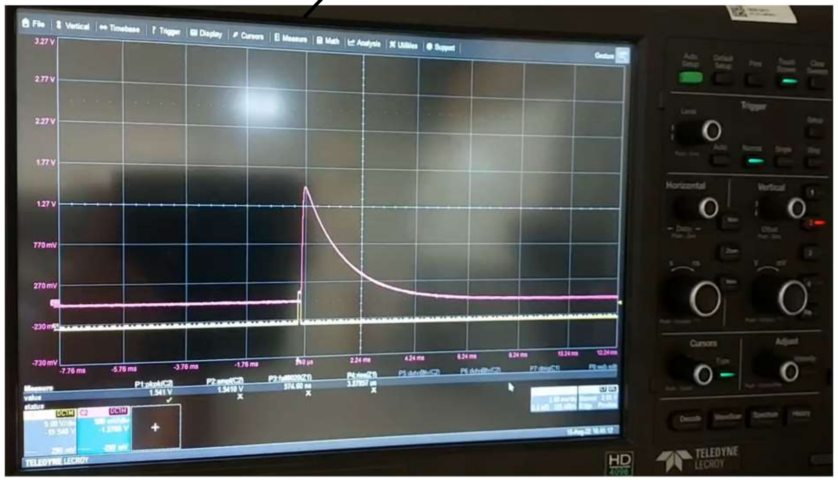


Beam at HIGH3.Scr2

Pyro signal at HIGH3.Scr2



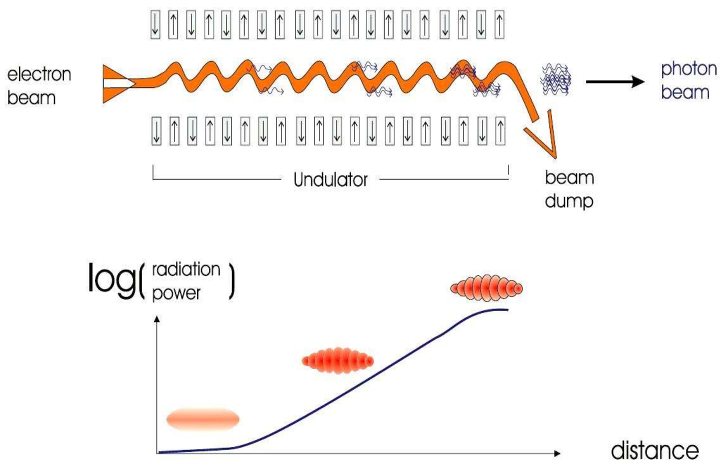
electrons



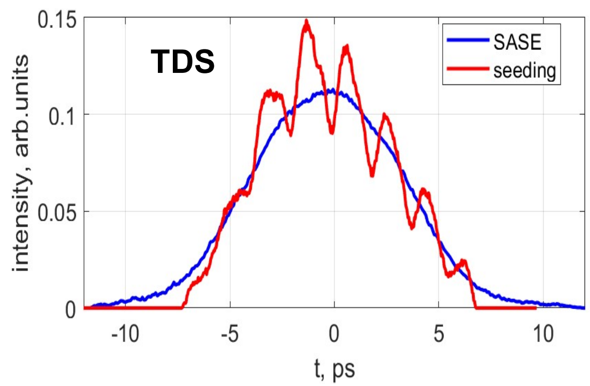
Courtesy: M.Krasilnikov

SASE gain curves and first seeding experiments

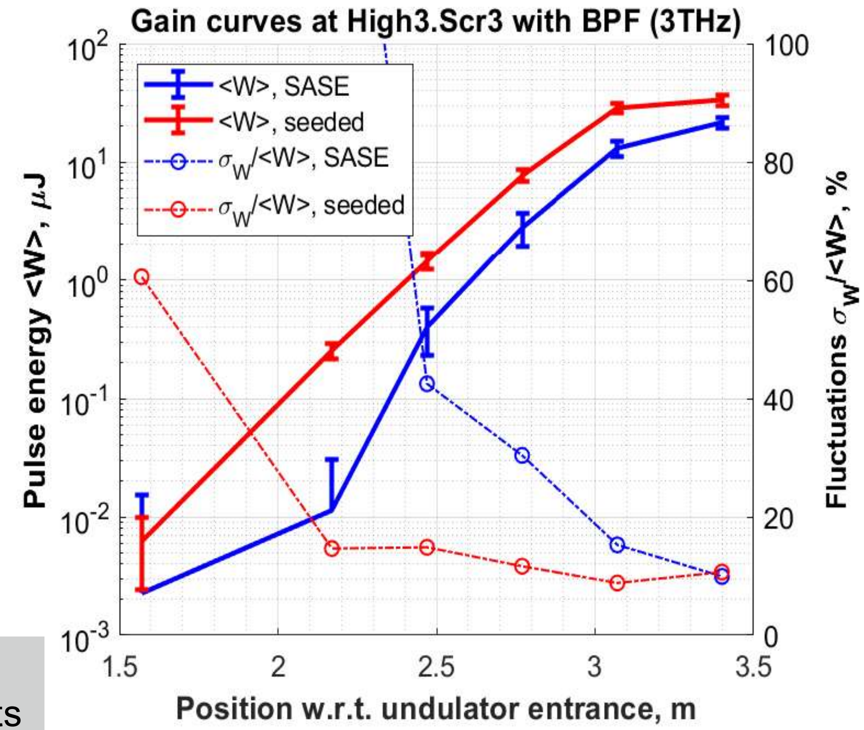
- measured FEL gain curves with band pass filter (3 THz)
- first seeding experiments at 2 nC with modulated electron beams
  - modulated photocathode laser pulse
  - observed **pulse energy increase**: 33μJ vs. 21μJ from SASE
  - gain curve starts earlier and is **more stable**



Free Electron Laser in the Self Amplified Spontaneous Emission (SASE) mode
Image: TESLA Technical Design Report Part I



Further studies (ongoing):
- FTIR spectrometer measurements
- imaging with THz pyro camera
- MIR commissioning



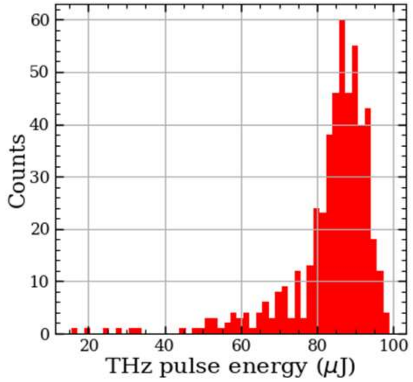
Courtesy: M.Krasilnikov

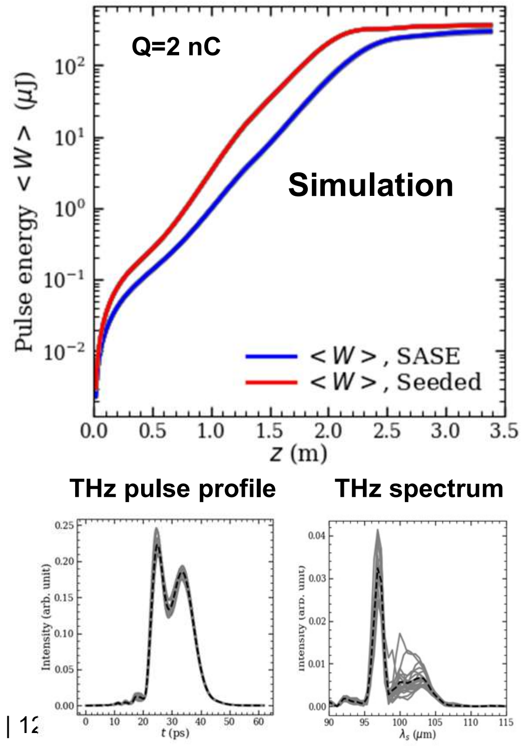
THz simulations and predicted performance

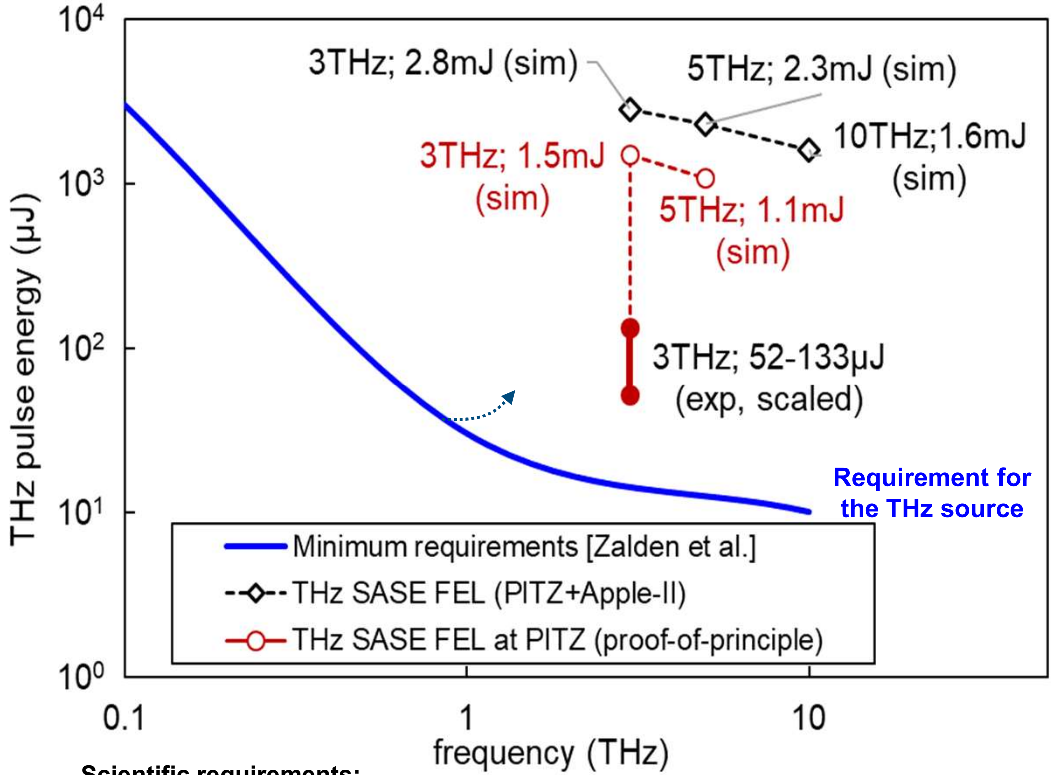
- Simulation of radiation process is very challenging (accurate initial noise modeling)
- Combine simulations and experimental results to predict possible performance (i.e. pulse energy)

Optimized 3THz pulse energy at 2.4 nC:
$(83.8 \pm 13.3)\mu J$

Estimated THz transmission: 49 % ➔ >100 μJ were produced



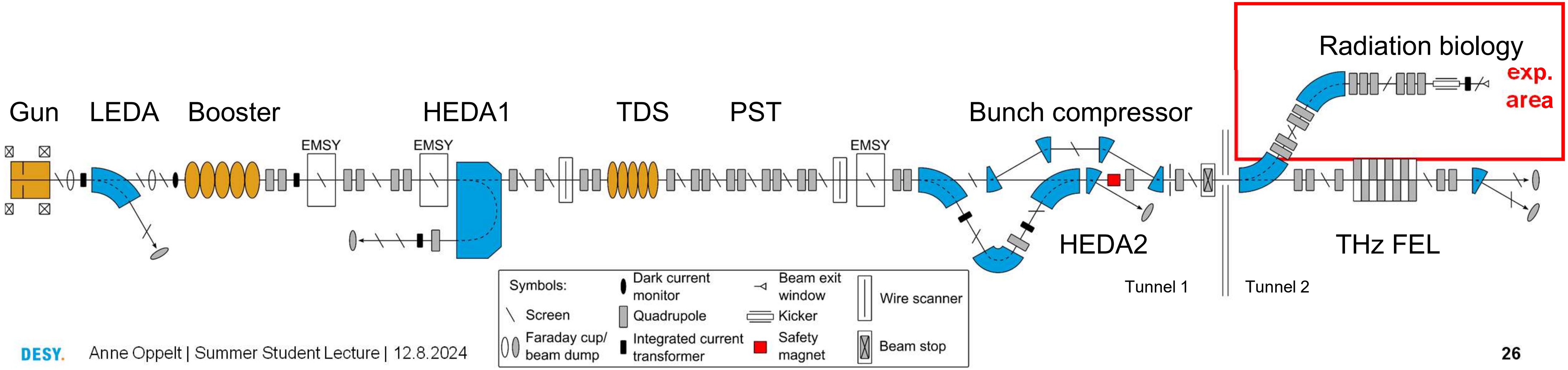




Scientific requirements:
[1] P. Zalden, et al., "Terahertz Science at European XFEL", XFEL.EU TN-2018-001-01.0
"...3 to 20 THz is the most difficult to cover by existing sources; at the same time, many vibrational resonances and relaxations in condensed matter occur at these frequencies."

Courtesy: M.Krasilnikov, X.Li

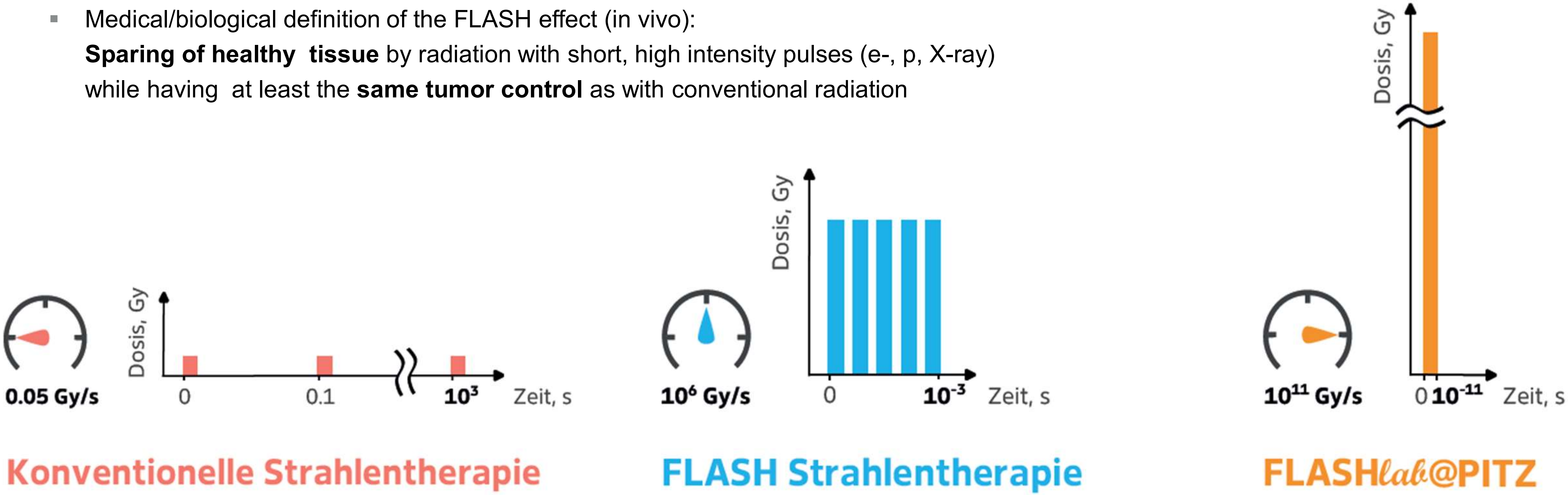
Radiation biology studies with FLASH*lab*@PITZ



Cancer treatment with radiation therapy

A new R&D platform for radiation biology and cancer research at PITZ

- cancer treatment by conventional radiotherapy treatment has strong side effects
- the FLASH effect may reduce the side effects for normal tissue
  - **experimentally proven observation**
  - 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, X-ray)
    while having at least the **same tumor control** as with conventional radiation



Courtesy: A.Grebinyk

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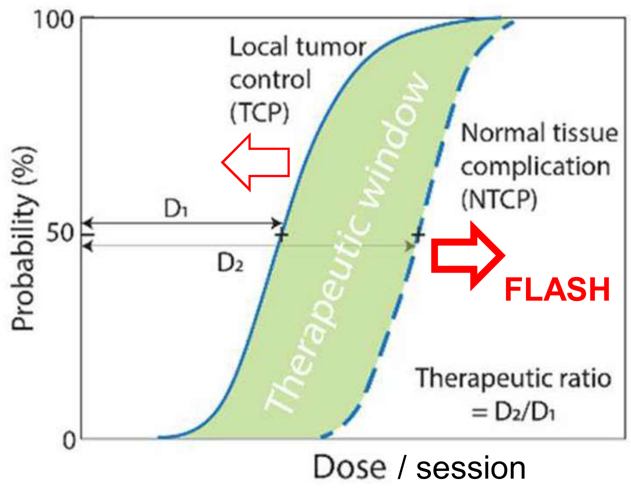


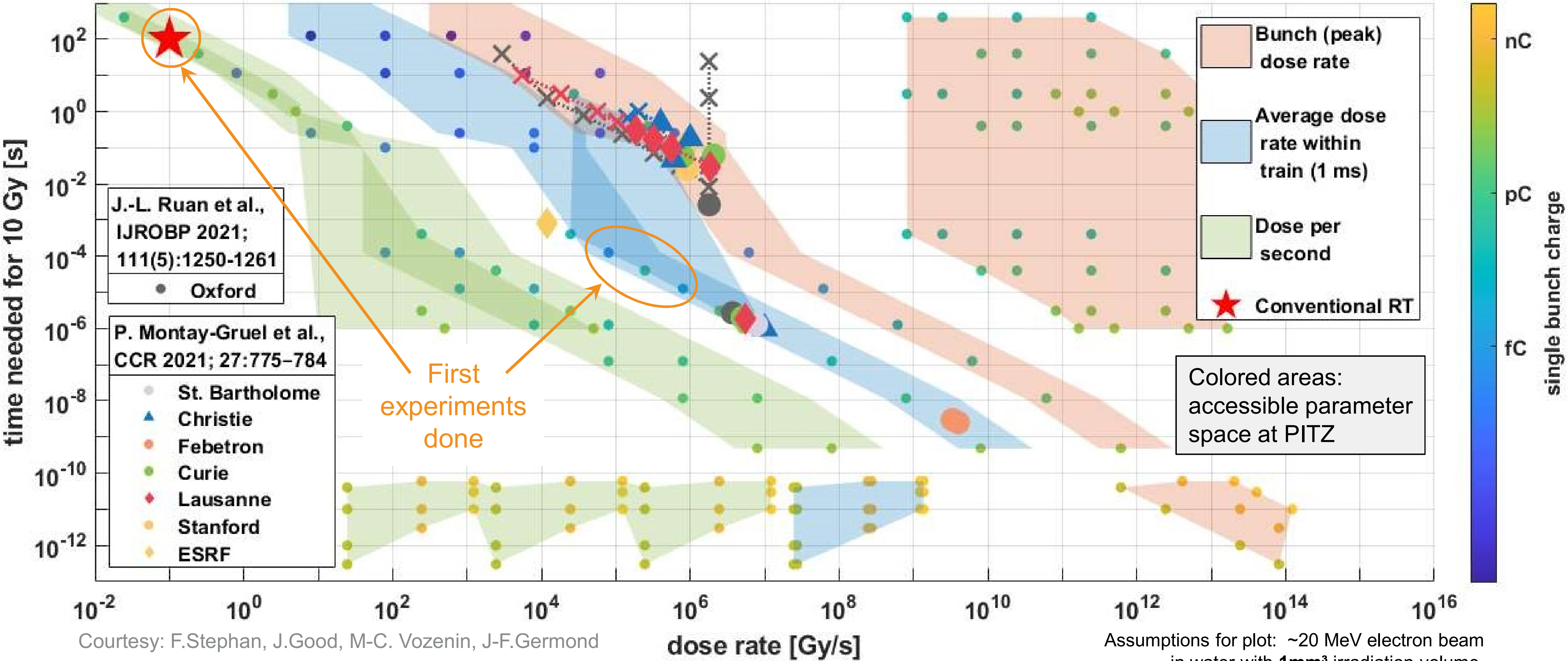
From M.R. Ashraf et al., Frontiers in Physics, 2020, doi: 10.3389/fphy.2020.00328

- PITZ is an ideal platform for R&D work
  - profit from the **unique parameter range** available from the PITZ accelerator with its manyfold **beam diagnostics** and **beam manipulation** possibilities
  - study radiation effects on cancer cells and normal tissue
  - conventional dose rates – FLASH effect – ultra high dose rates (UHDR)
  - detailed methodical studies up to preclinical tests
- New dedicated beamline with a flexible experimental area for biological and bio-chemical experiments is being installed in the PITZ tunnel extension

Courtesy: F.Stephan

Parameter space available at PITZ

PITZ can cover the full range from conventional RT via state-of-the-art FLASH to yet unexplored high dose levels
→ unique R&D on FLASH radiation therapy



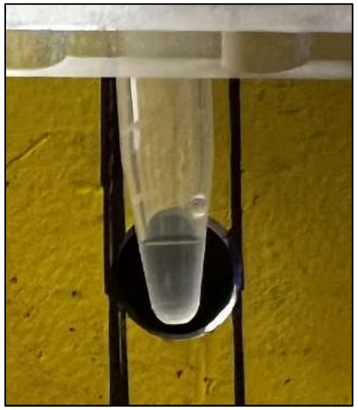
Courtesy: F.Stephan, J.Good, M-C. Vozenin, J-F.Germond

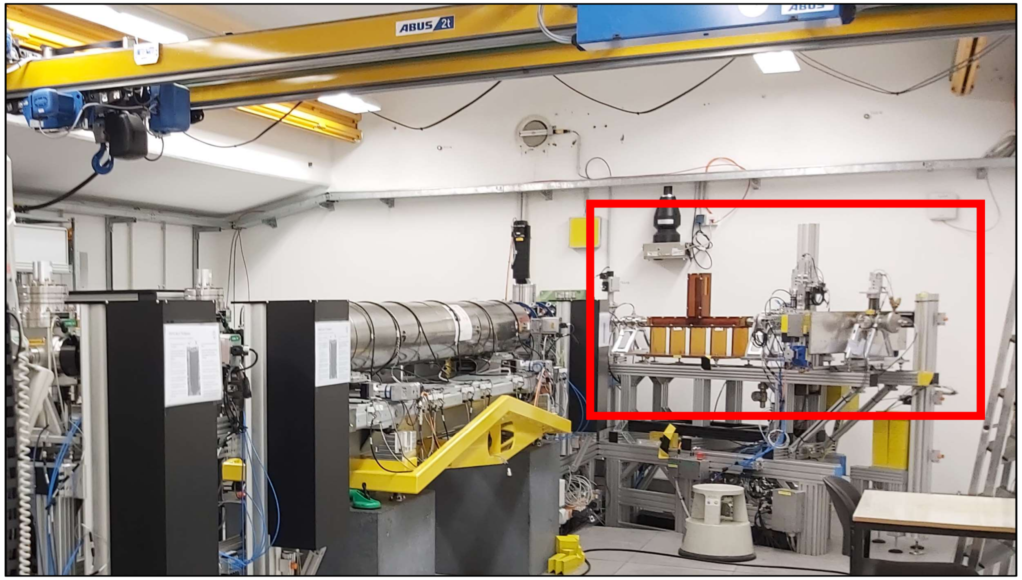
Assumptions for plot: ~20 MeV electron beam in water with **1mm³** irradiation volume.

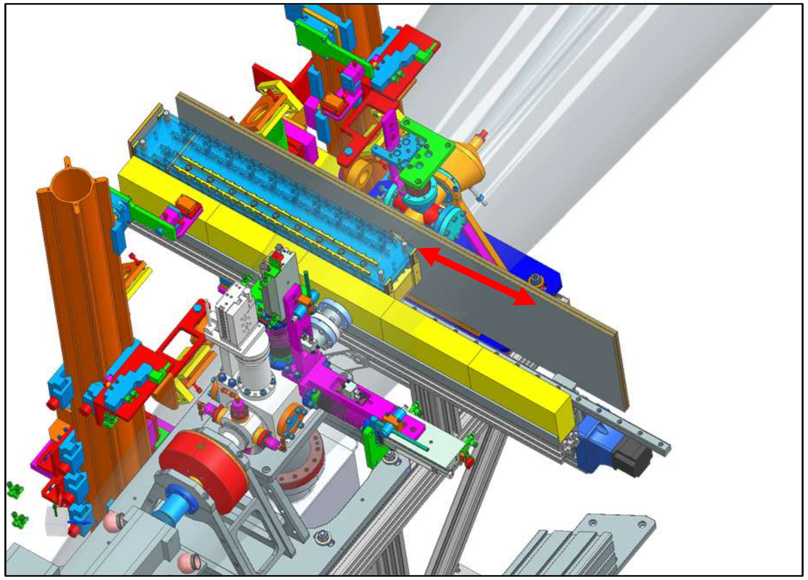
Current (preliminary) experimental setup

A beamline for first basic studies

- in autum 2022, a **preliminary beamline** was set up from available (spare) components
- for experiments, a movable stage for Eppendorff tubes was provided by TH Wildau, and a water phantom was given by U Manchester
- **first successful studies**: beam characterization, dosimetry, irradiation of different cell samples
- suffer from insufficient beam diagnostics and control → a dedicated beamline is needed





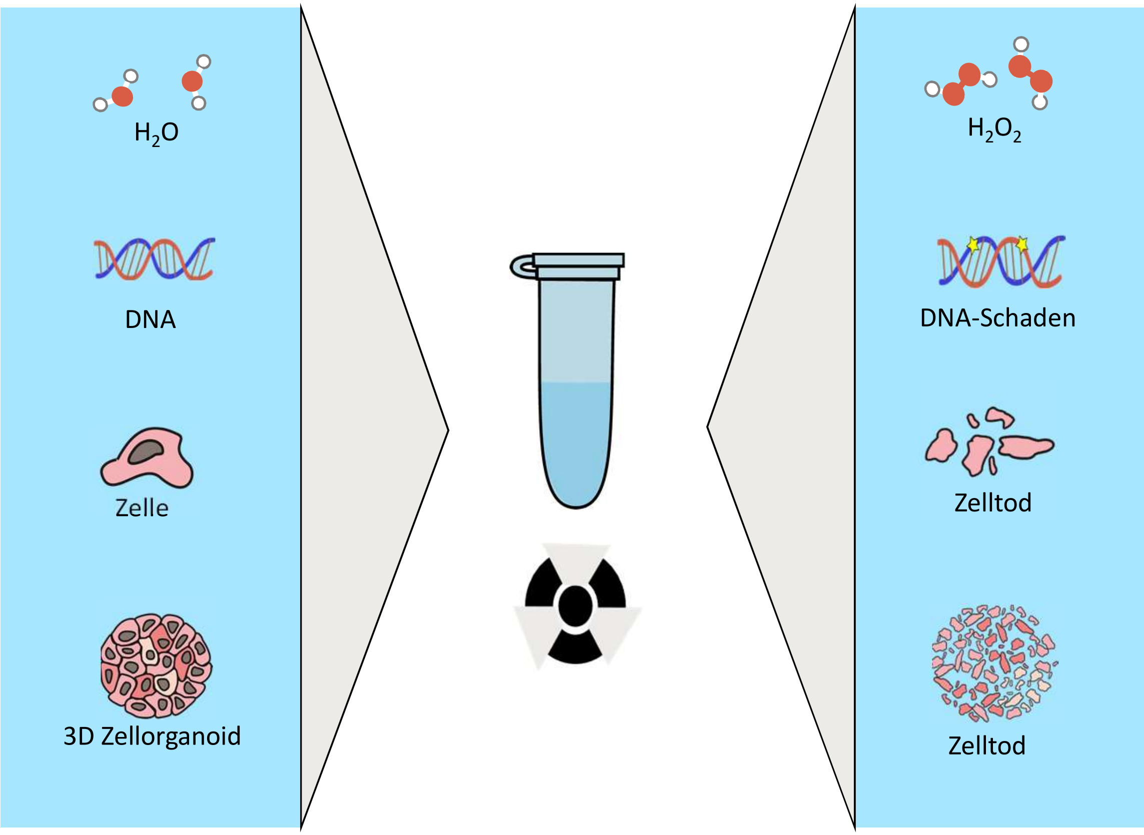


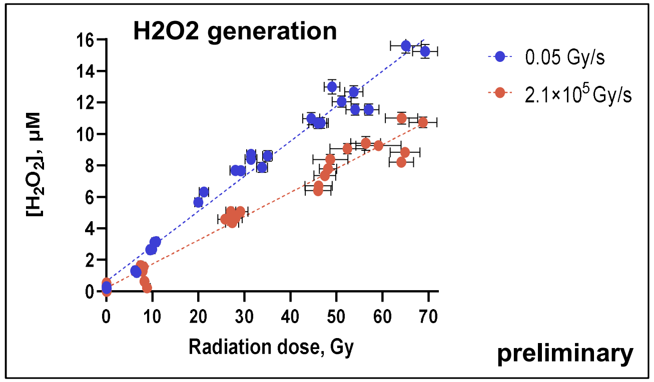
Courtesy: F.Müller, A.Grebinyk

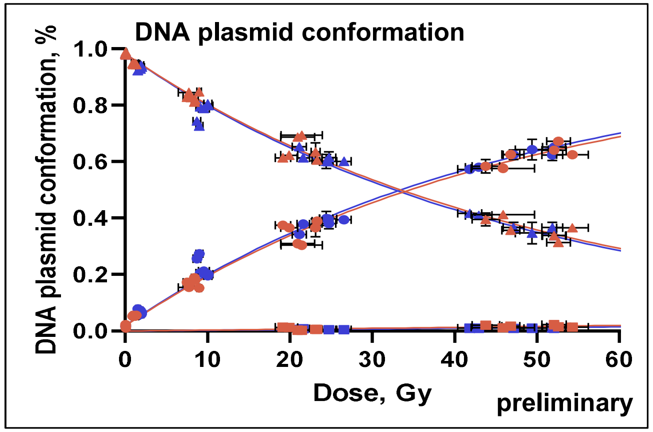
First in-vitro experiments at PITZ

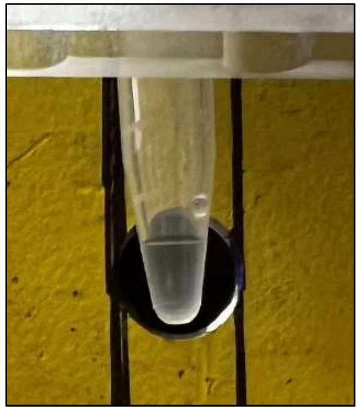
Irradiation of chemicals, biochemicals, healthy tissue, and cancer cells

- irradiation of probes provided by different collaboration partners with different dose levels (low – high – ultra high dose rate; single pulse - pulse trains of different time structures)









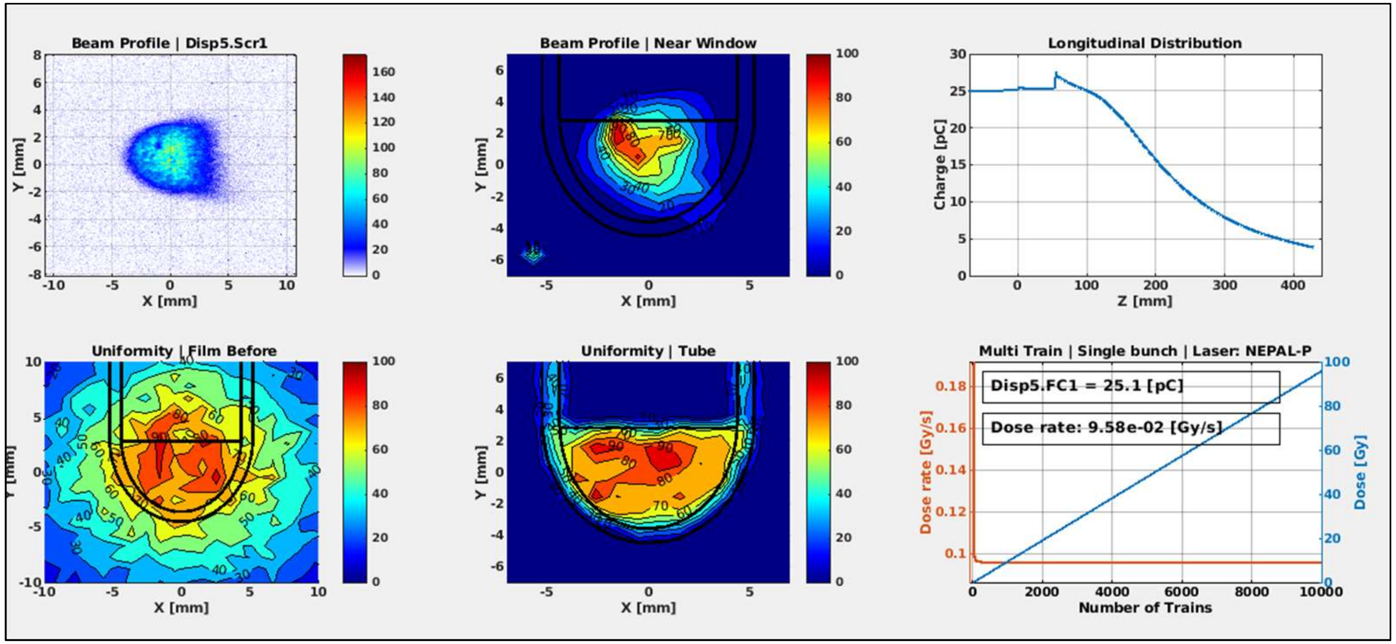
Courtesy: A.Grebinyk, F.Riemer

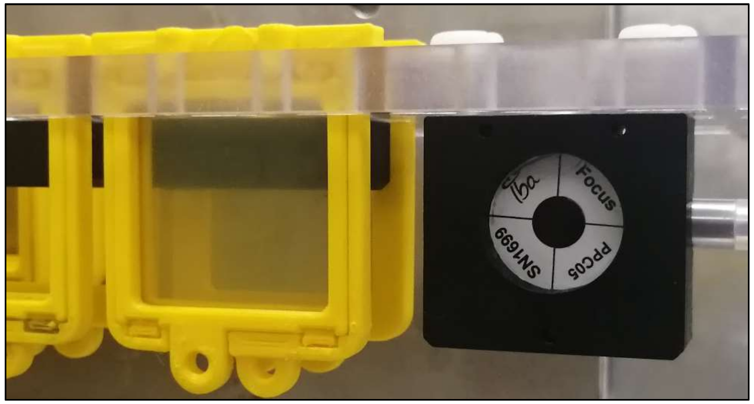
Dosimetry developments

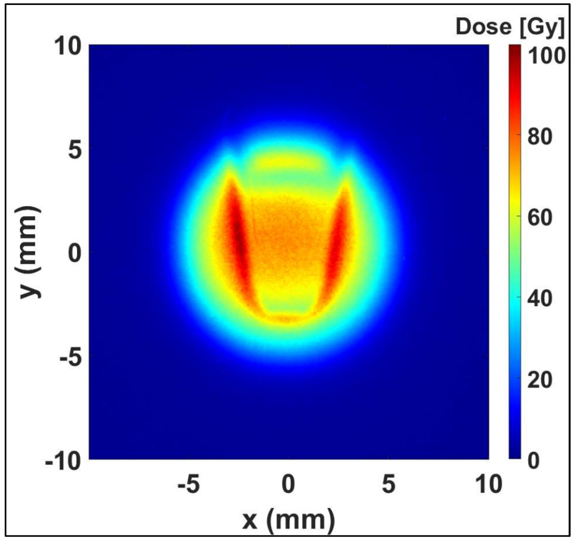
Online prediction and online measurement

- dose measurements with Gafchromic films and ionisation chamber
- online-monitoring of beam position and beam distribution as simulation input
- development of new detectors for ultra-short pulses and ultra-high dose rates

Online FLUKA simulation (~2 minutes)







Courtesy: F.Riemer

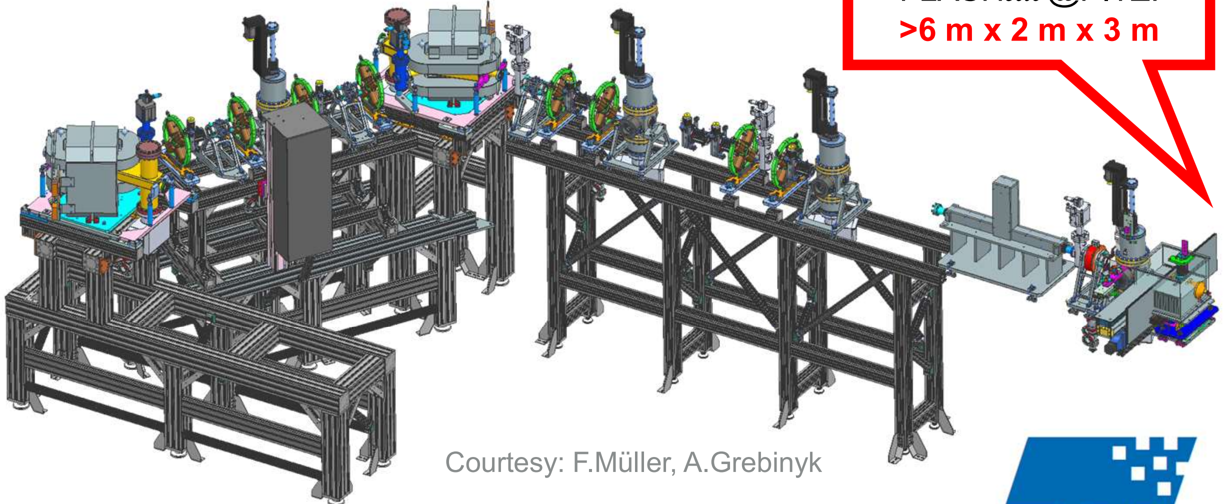
Planned activities at FLASH*lab*@PITZ

Dedicated beamline setup for radiation biology R&D

Laboratory container for chemical and biological experiments

- require components for **detailed beam control and survey**: charge, beam size and position, stability, dose distributions, …
- test **new developments** like a fast kicker and dosimetry tools
- experimental area with **high flexibility** to allow for manifold experiments:
  - moving stage with Eppendorff tubes (as already tested)
  - water phantom (as already tested)
  - test of different devices for dosimetry
- Strong collaboration with many new partners in the bio-medical sector:
  - Experiments in collaboration with new partners, e.g. TH Wildau, U Manchester, Charite Berlin, U Potsdam, …
  - Coordination with **external users** has started e.g. with HZDR, UniBw München, …

Experimental area for FLASH*lab*@PITZ: **>6 m x 2 m x 3 m**



Courtesy: F.Müller, A.Grebinyk

Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG · Universität der Bundeswehr München · CHARITÉ UNIVERSITÄTSMEDIZIN BERLIN · CHUV Lausanne · PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin · UHDpulse · CANDLE · TH WILDAU

Summary

- The spectrum of **research topics at PITZ** has extended over the last years, thanks to the **large flexibility of beam parameters** and manyfold **beam diagnostics techniques**
- Basic research program: photoinjector physics (**guns**, cathodes, stability, FEL-related issues)
- R&D activities on **photoinjector applications**, e.g.
  - beam driven plasma acceleration
  - THz SASE FEL
  - FLASH radiation therapy and radiation biology
- PITZ is a big **team work** experiment with contributions from many sides
  - DESY colleagues from different groups at **Zeuthen** and **Hamburg**
  - **25 national and international partners**
    AANL(YERPHI) + CANDLE Yerevan, Charité Berlin, CHUV Lausanne, DKFZ Heidelberg, HZB Berlin, HZDR Rossendorf, ICR London, IAP RAS Nizhny Novgorod, IJCLab Orsay, INFN Frascati & Uni Roma, INFN LASA Milano, INRNE Sofia, INR Moscow, JINR Dubna, LBNL Berkeley, MBI Berlin, PTB Braunschweig, SLAC Stanford, ThEPCenter Chiang Mai, TH Wildau, TUD-TEMF Darmstadt, UHH Hamburg, UKRI Daresbury, UniBW München

PITZ – a collaborational success

International group of physicists in close collaboration with engineers and technicians

2002

2005

2011

2015

2017

2019

2022