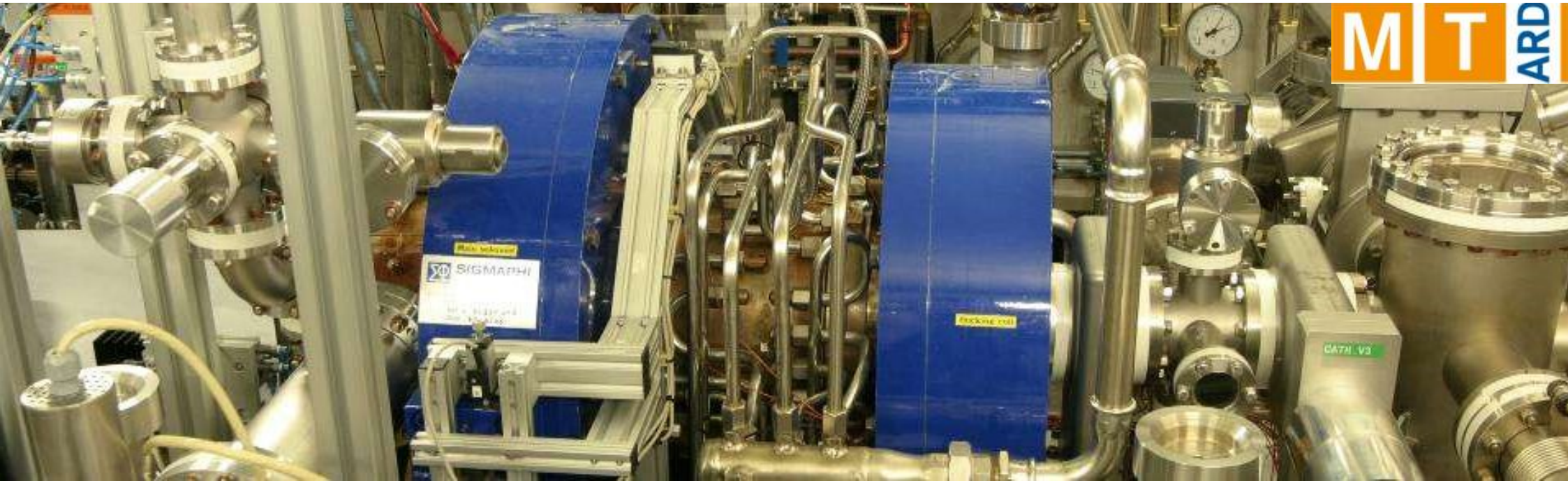


Status of the PITZ facility

Photoinjector R&D and applications

Anne Oppelt

12th MT ARD ST3 Meeting 2024 in Darmstadt

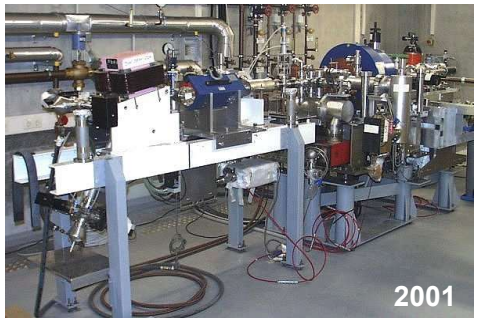
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

PITZ Photo Injector Test Facility Zeuthen

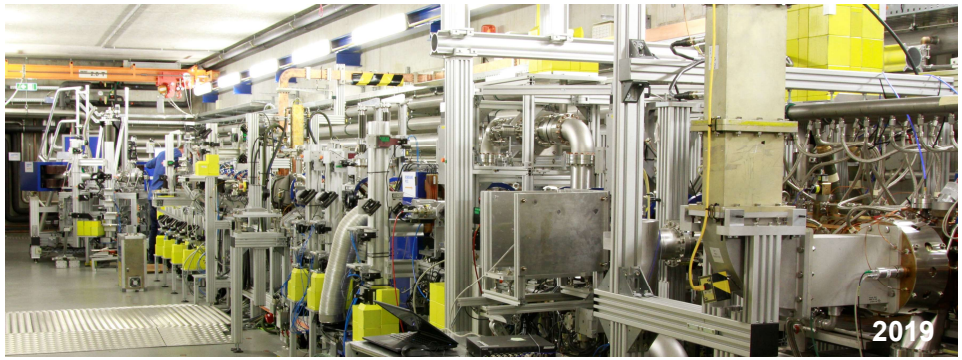
DESY.

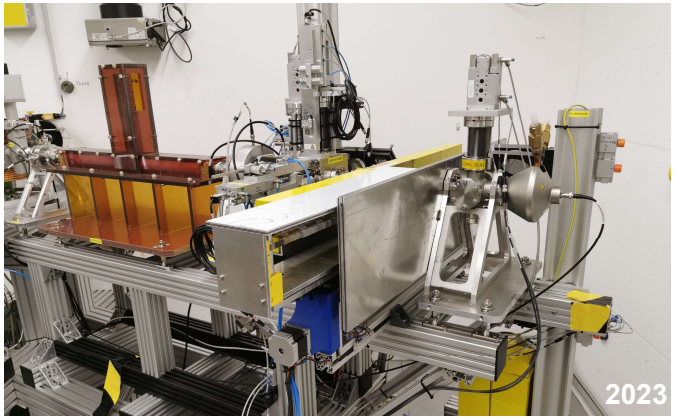
Photo Injector Test facility in Zeuthen

PITZ 1999-2024



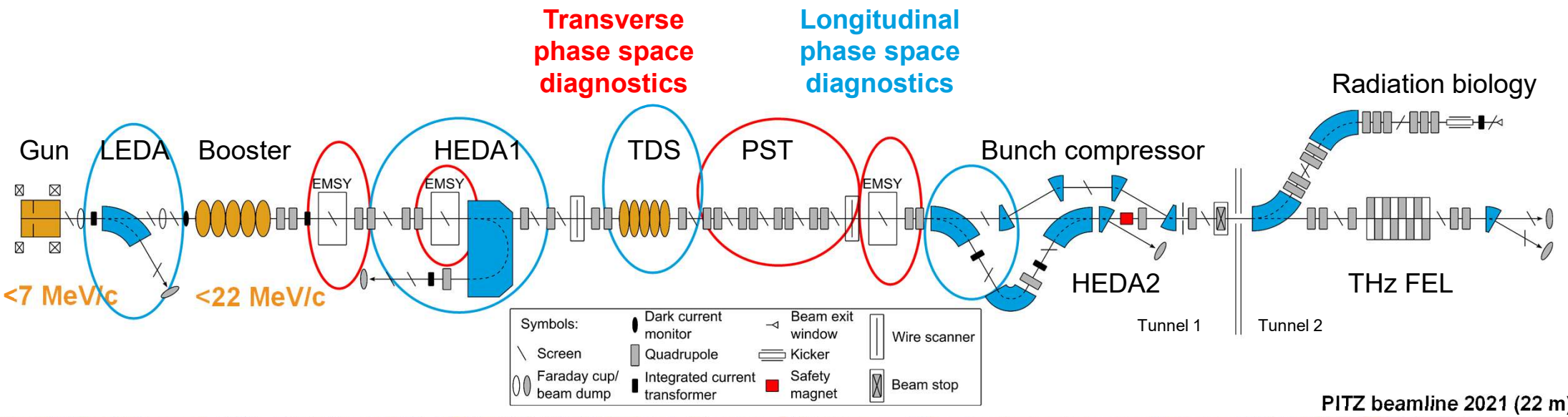
- **Original purpose:** development, optimization and delivery of electron sources for user facilities at DESY in Hamburg (FLASH and European XFEL)
- PITZ has been extended several times and developed meanwhile into much more than a test stand for electron sources
- **Applications** of high brightness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





Facility overview

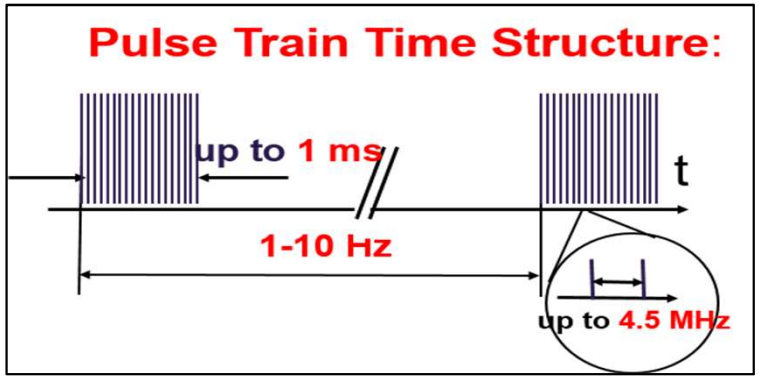
- normal conducting 1.3 GHz RF gun and booster
- lots of beam diagnostics + beam manipulation capabilities
- continuous improvements of all **subsystems** to optimize beam quality and stability

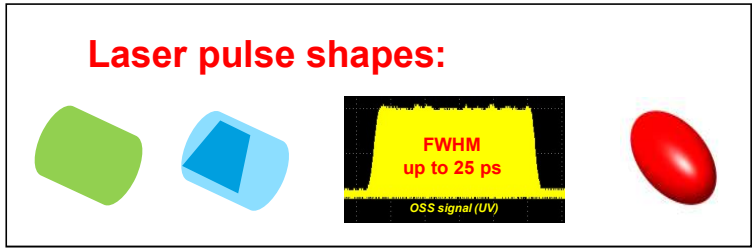


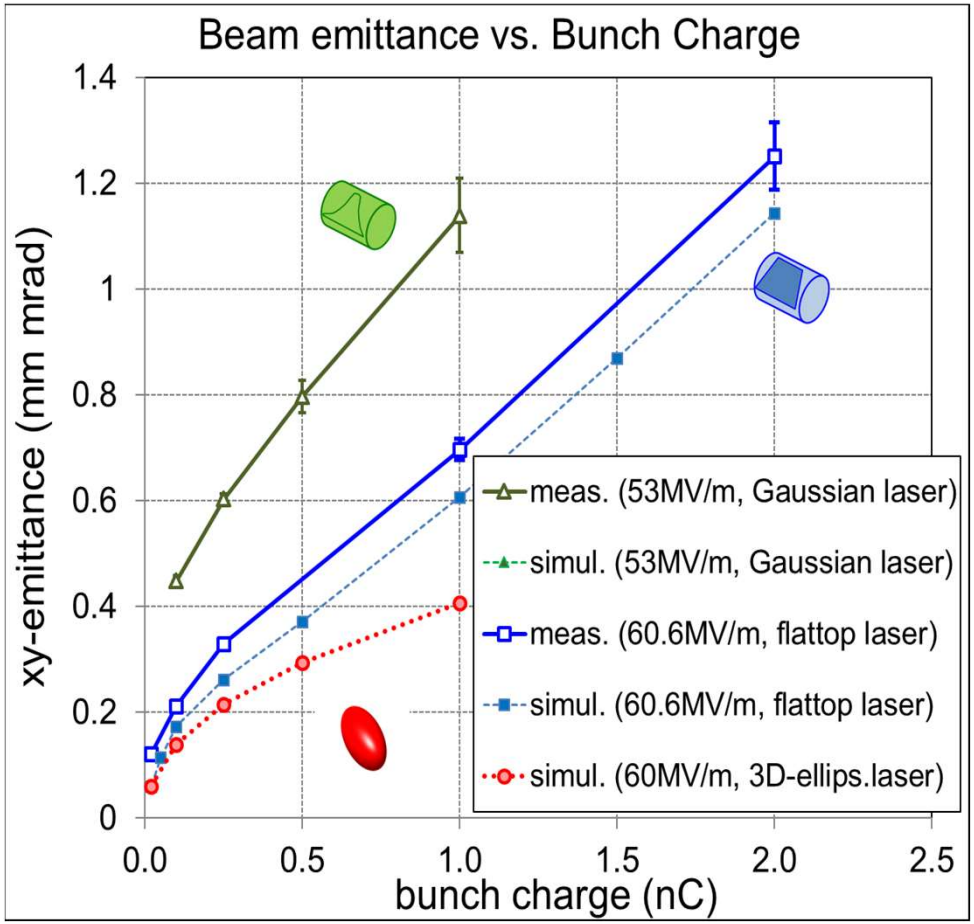
PITZ beamline 2021 (22 m)

Generation of high brightness electron beams

- European XFEL pulse train structure with up to 27000 buches per second
- photocathode laser system (λ=257nm) with advanced temporal (micro) pulse shaping
- emittance optimization to drive European XFEL





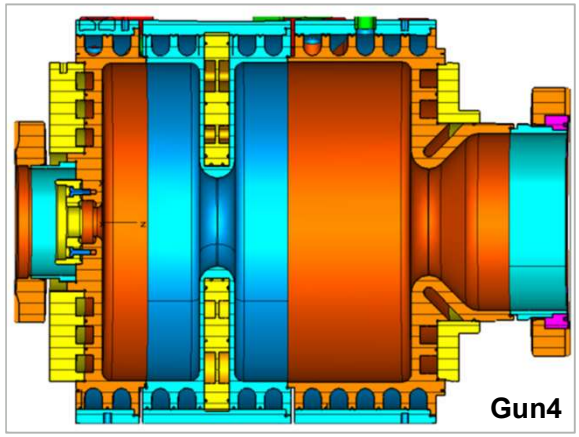


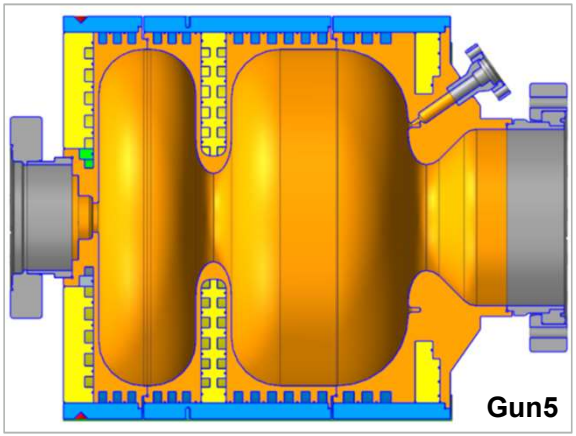
Courtesy: M.Krasilnikov

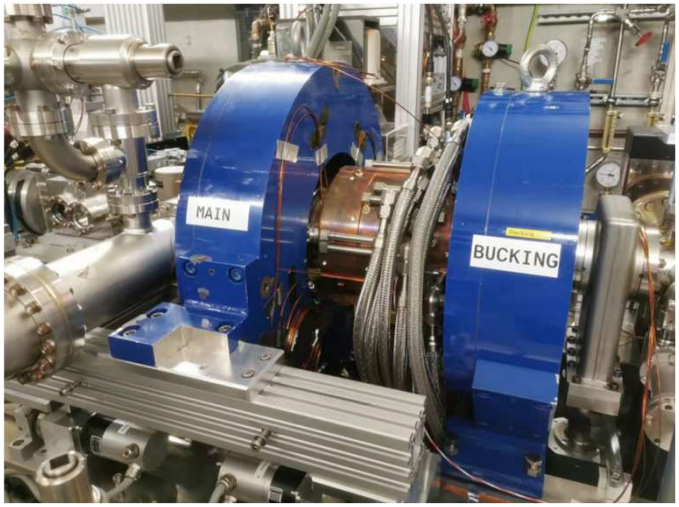
M. Krasilnikov et al., PRST-AB 15, 1000701 (2012).

Gun development for FLASH and European XFEL

- In total, 10 different electron 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

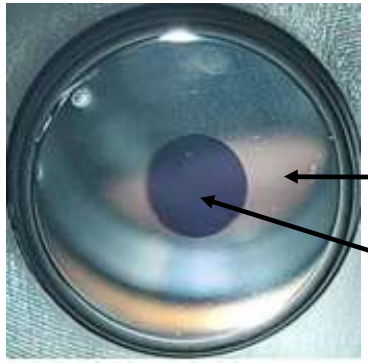

Gun5



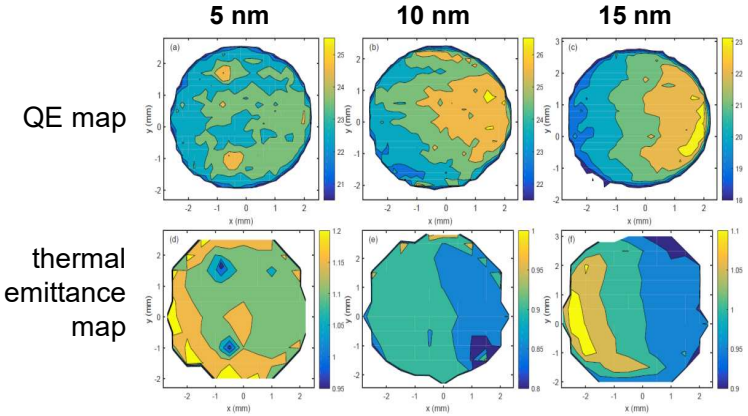
Gun5.1

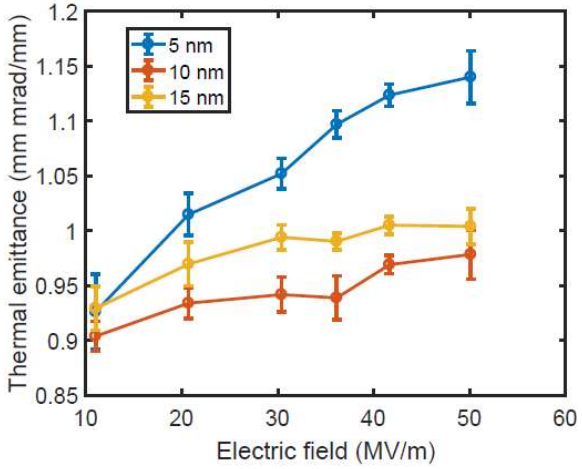
Photo cathode developments

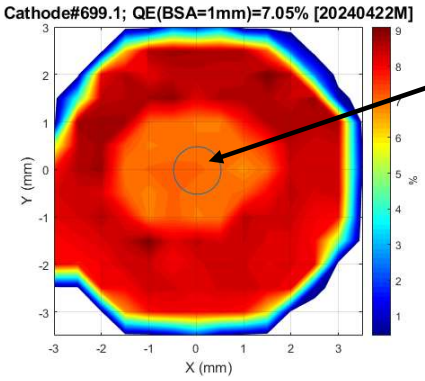
- to date **Cs_2Te cathodes** used; **UV laser** system (λ=257nm) required
  - **Advantages**: low dark current, high life time + robustness
  - standard production for DESY's facilities (EuXFEL, FLASH, PITZ) is done at DESY in Hamburg
  - special cathodes for R&D studies are developed by INFN LASA Milano



Front view of a photo cathode







QE map of a used Cs_2Te cathode

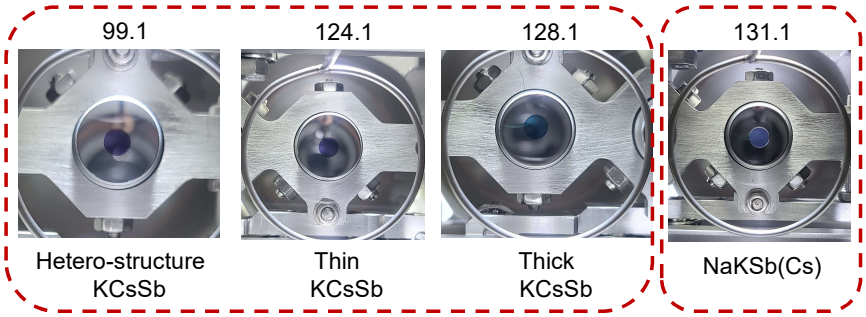
Example: Cs_2Te cathodes with different Te thicknesses were tested
=> anti-correlation between QE and thermal emittance observed

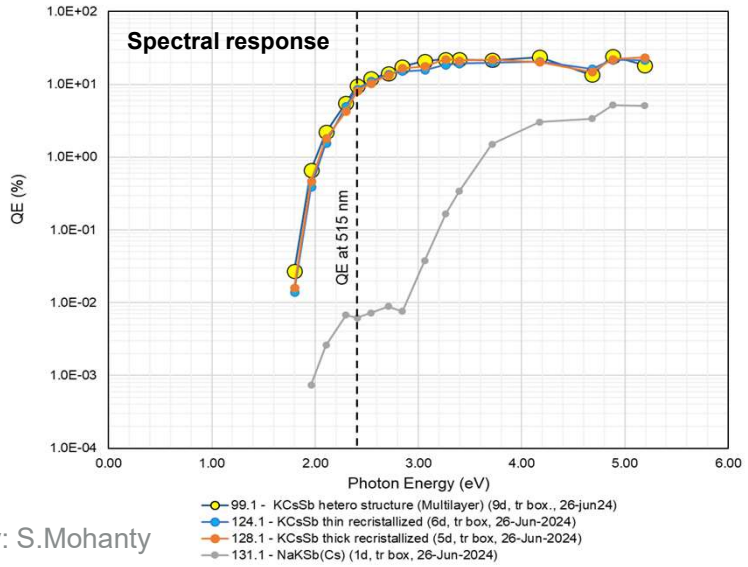
Courtesy: F.Stephan

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

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
  - cathodes were sent to PITZ last Monday and will be tested within the next weeks
- Further planned investigations
  - cathode degradation studies
  - surface characterization studies
  - …

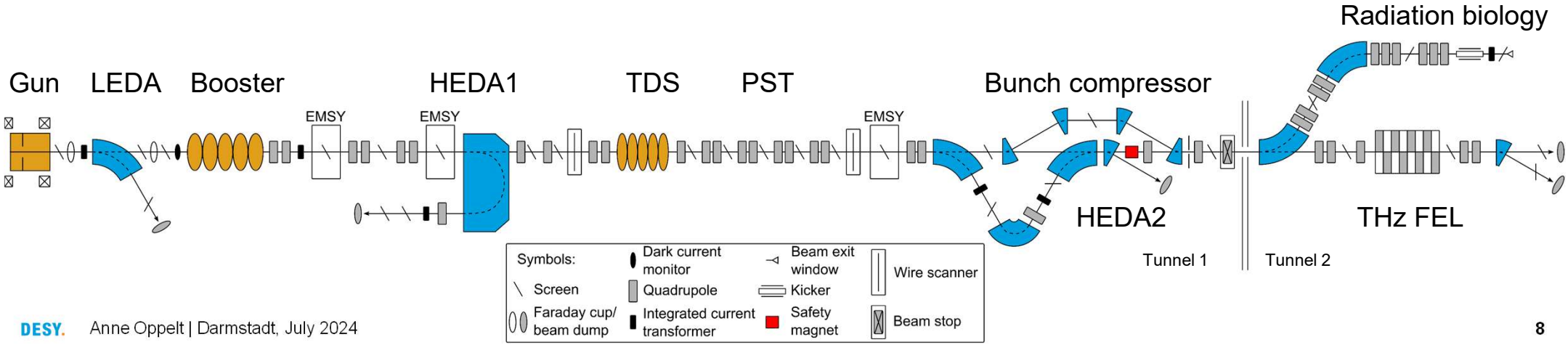




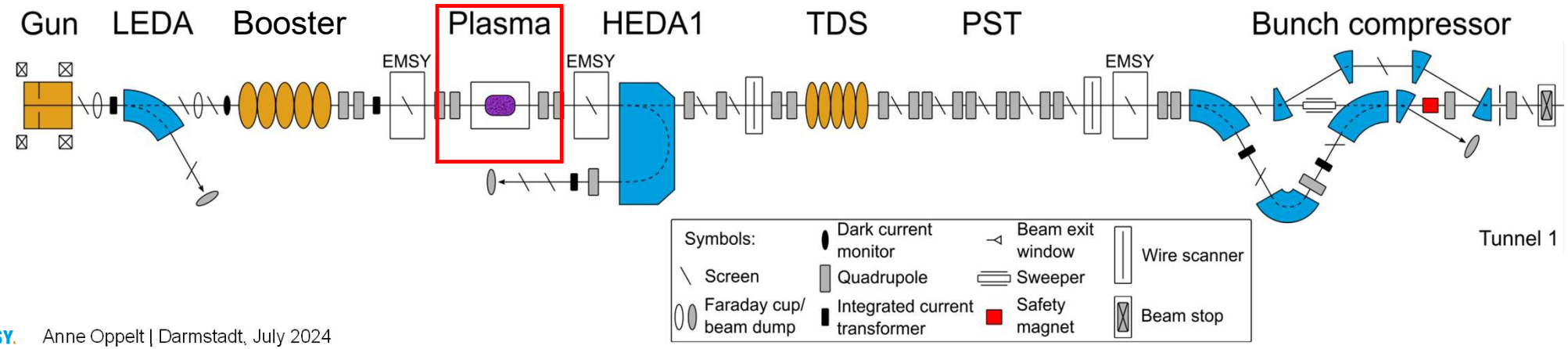
Courtesy: S.Mohanty

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

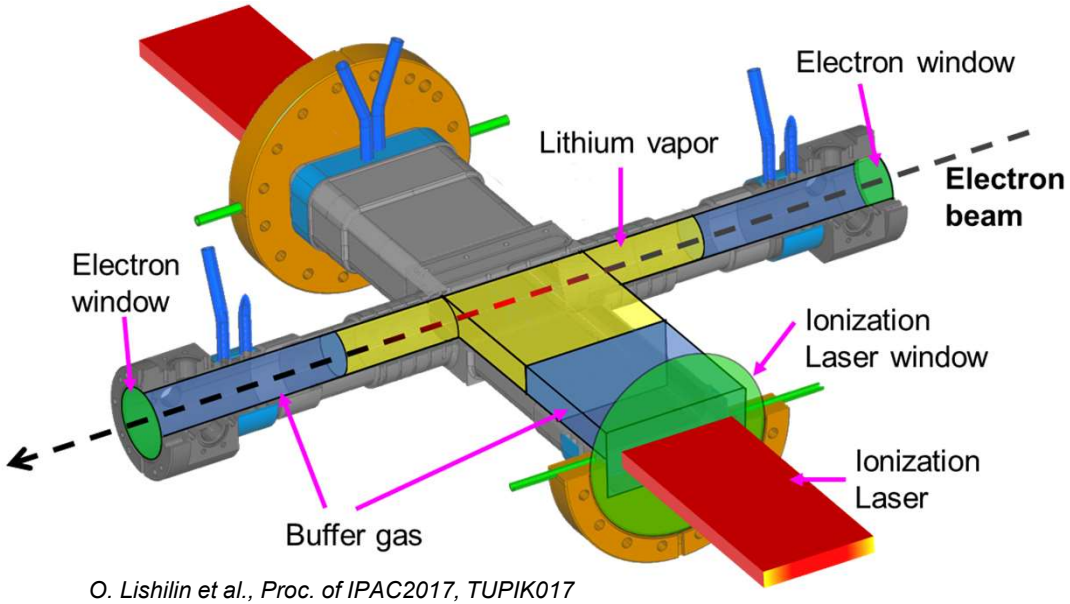


R&D on beam driven plasma acceleration

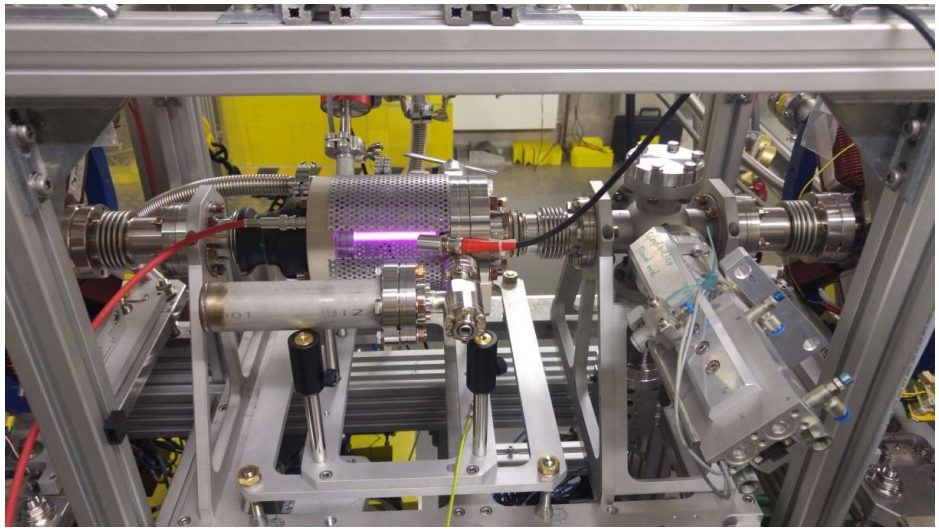


R&D on beam driven plasma acceleration

- 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



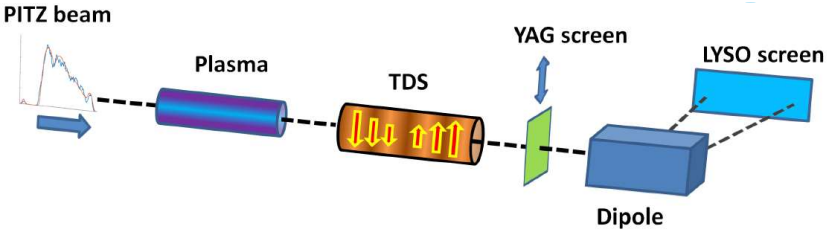
O. Lishilin et al., Proc. of IPAC2017, TUPIK017



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

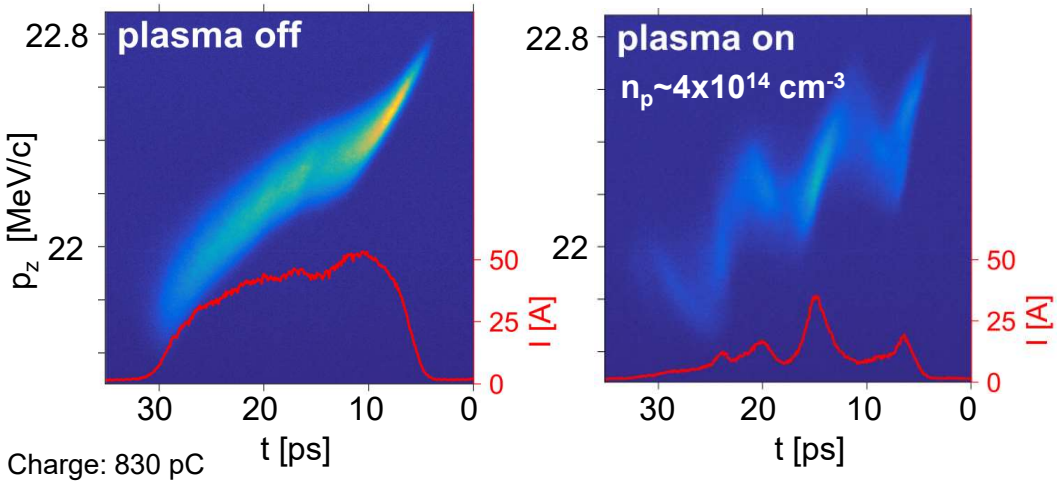
Beam driven PWFA Research at PITZ

… 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

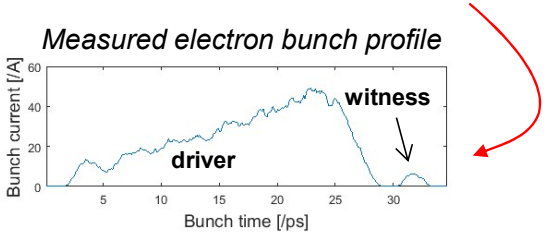


Charge: 830 pC
Plasma density: ≈10^{14} cm^{-3}

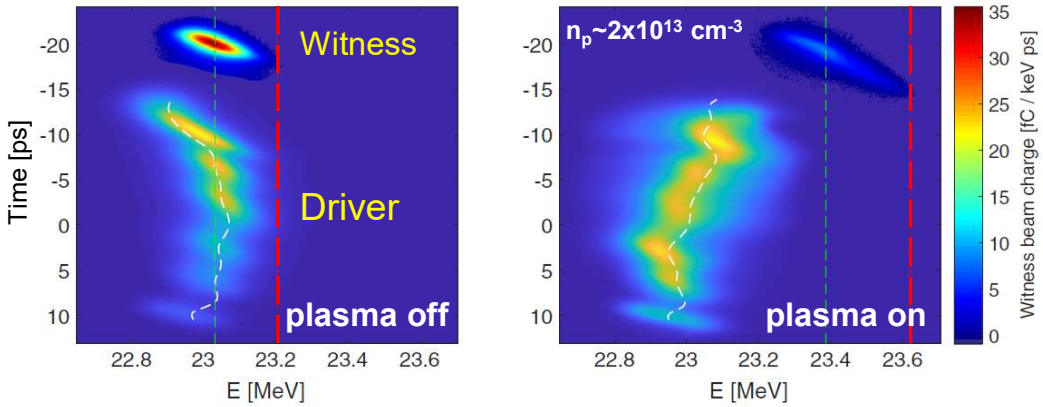
M. Gross et al., Phys. Rev. Lett. ***120****, 144802 (2018)*

➢ 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

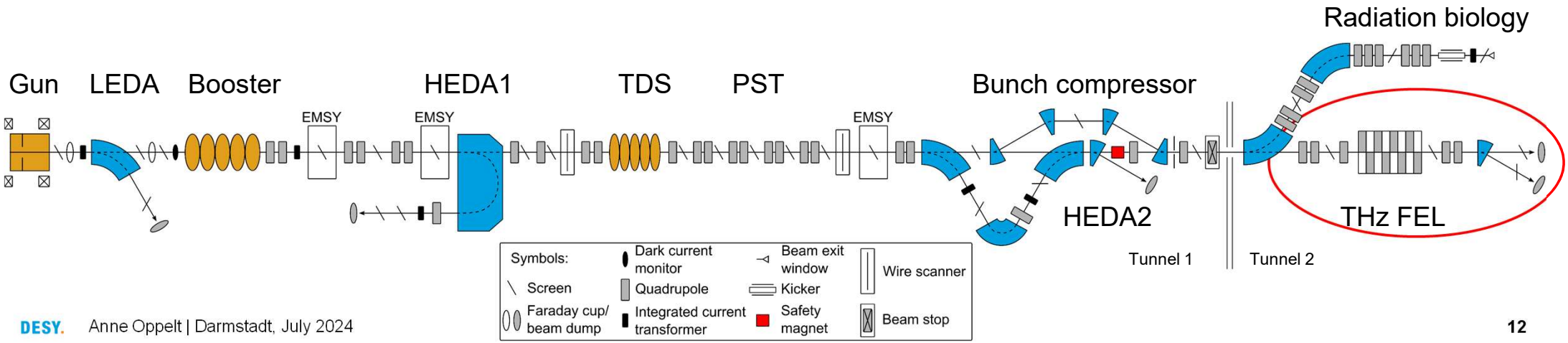


$$TR = 4.6^{+2.2}_{-0.7}$$



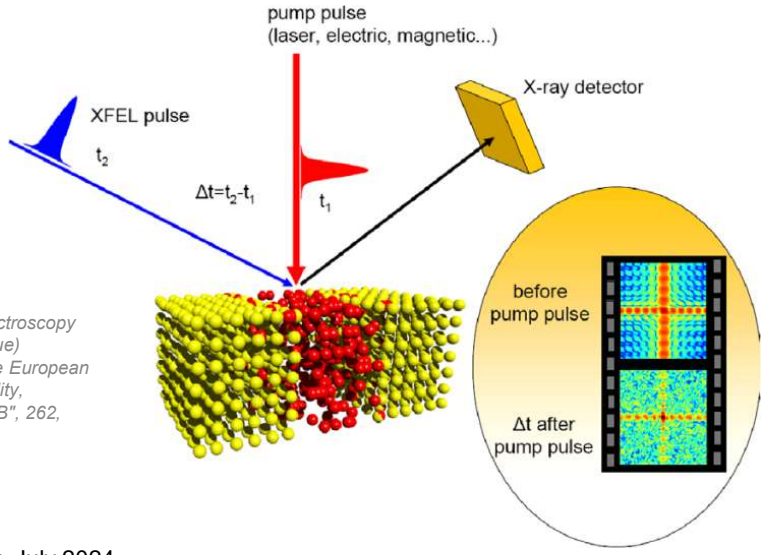
G. Loisch et al., Phys. Rev. Lett. ***121****, 064801 (2018)*

Proof-of-principle THz SASE FEL at PITZ

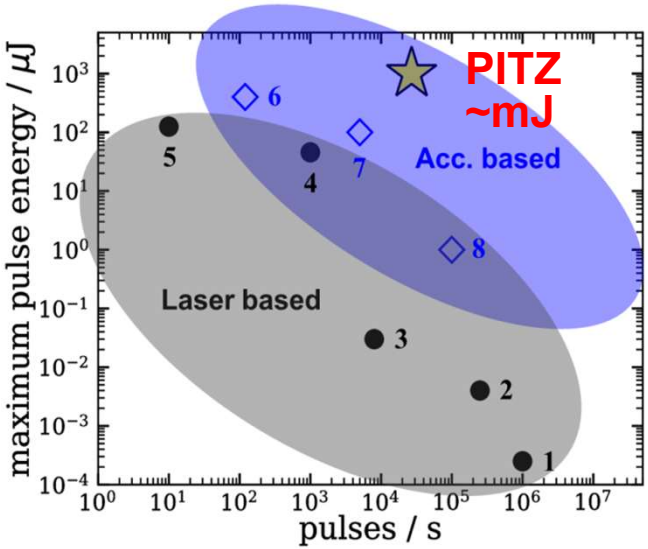


Pump-probe experiments with THz radiation

- 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)



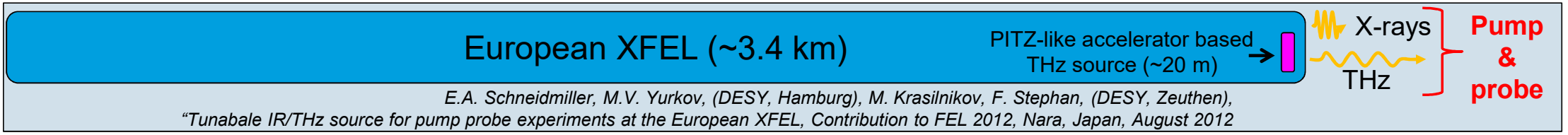
X-ray photon correlation spectroscopy (XPCS pump–probe technique) G. Grübel et al. "XPCS at the European X-ray free-electron laser facility, Nucl. Instrum. and Methods B", 262, 357-367 (2007).



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



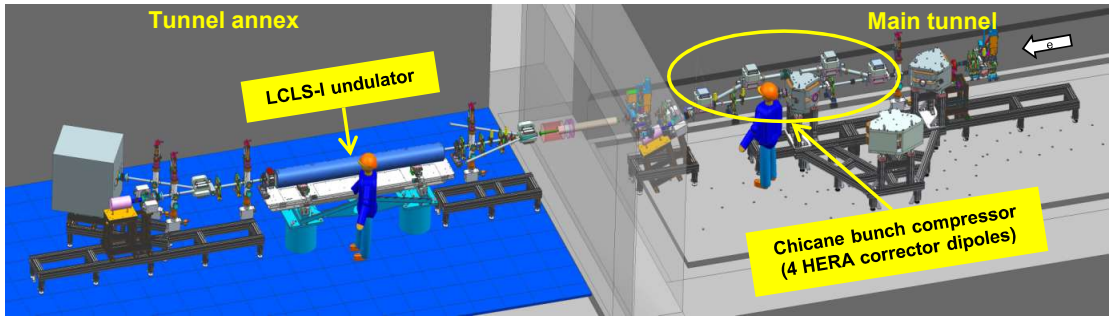
E.A. Schneidmiller, M.V. Yurkov, (DESY, Hamburg), M. Krasilnikov, F. Stephan, (DESY, Zeuthen),
"Tunabale IR/THz source for pump probe experiments at the European XFEL, Contribution to FEL 2012, Nara, Japan, August 2012

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

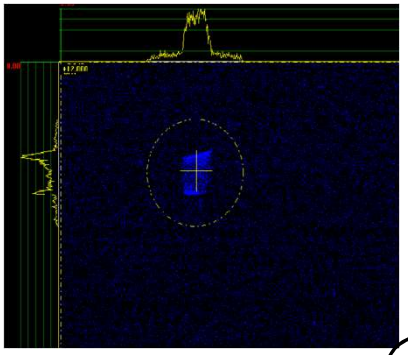
THz SASE FEL: from design to technical installation

- 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

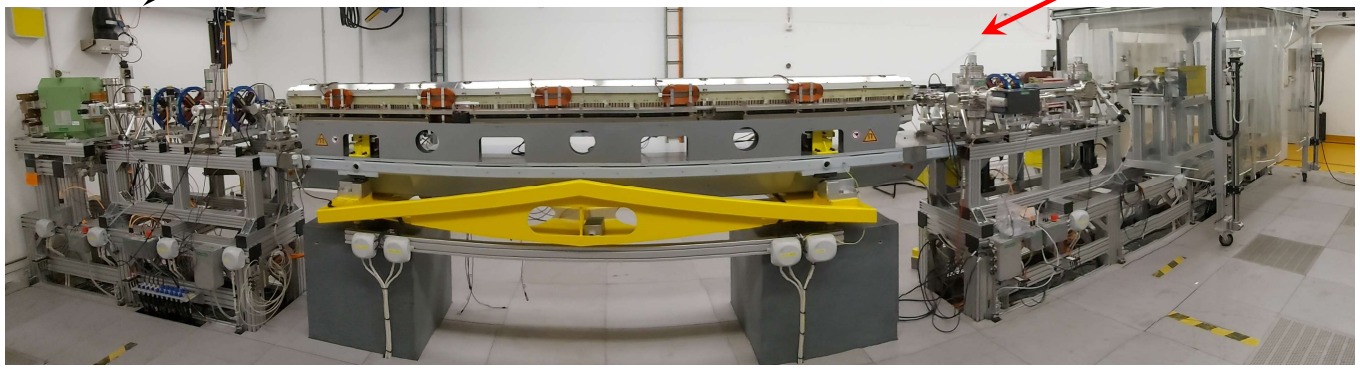
- installations and commissioning of components was done step by step
- **first beam** downstream the undulator detected on July 22 around 04:30
- **first lasing** on 9.8.2022 (1 nC, 17 MeV/c)
- **inauguration** of the THz FEL with Brandenburg‘s ministry for research on 28.11.2022



Beam at HIGH3.Scr2

Pyro signal at HIGH3.Scr2

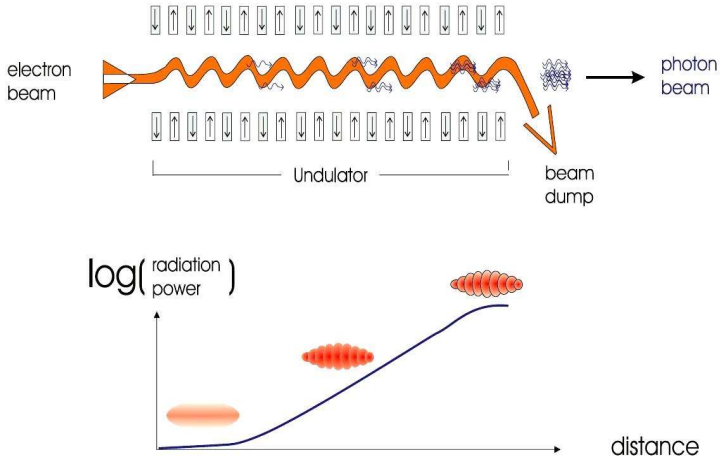
electrons



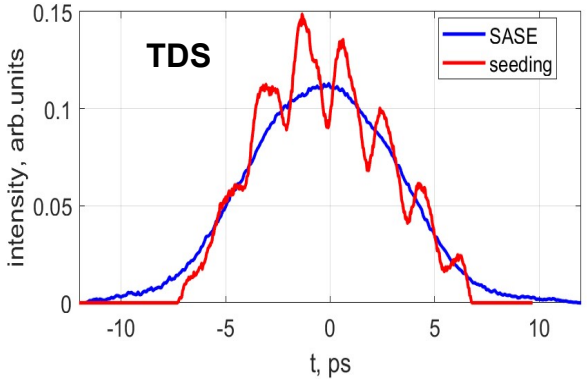
Courtesy: M.Krasilnikov

SASE gain curves and first seeding experiments

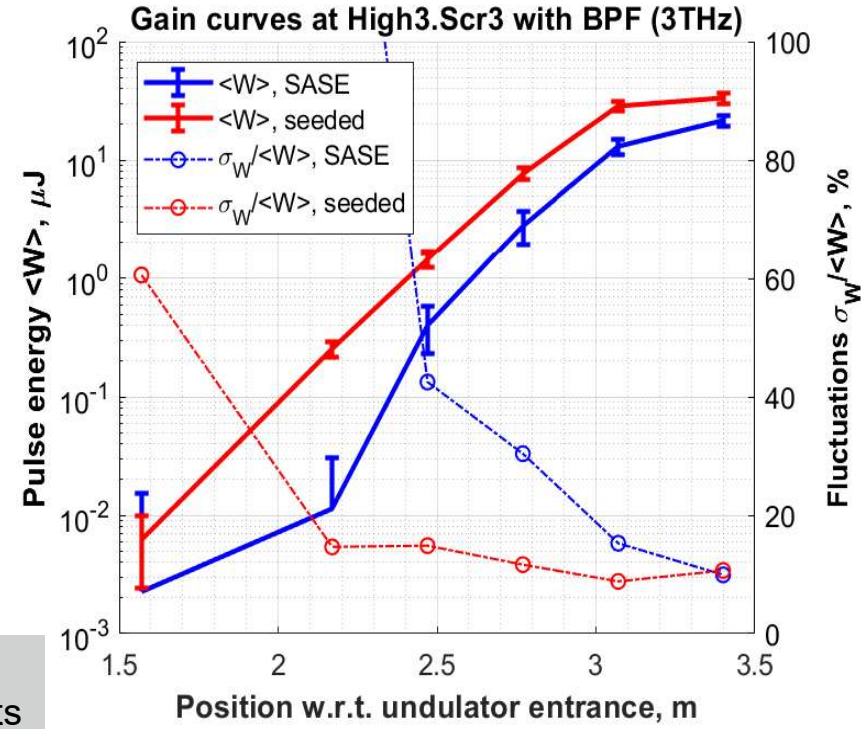
- measured FEL gain curves with band pass filter (3 THz)
- first seeding experiments at 2 nC with modulated electron beams
  - modulated photocathode laser pulse
  - observed **pulse energy increase**: **33µJ** vs. **21µJ** from SASE
  - gain curve starts earlier and is **more stable**



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



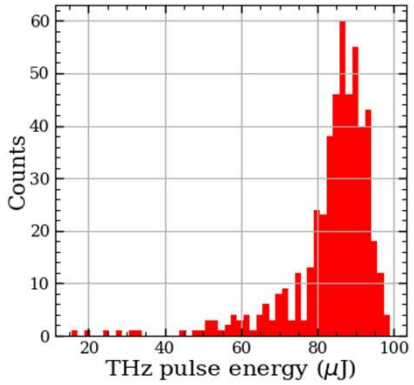
Courtesy: M.Krasilnikov

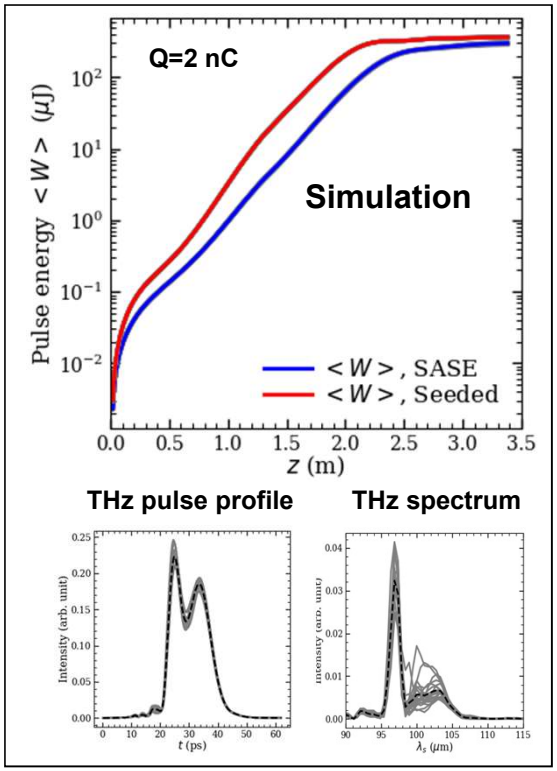
THz simulations and predicted performance

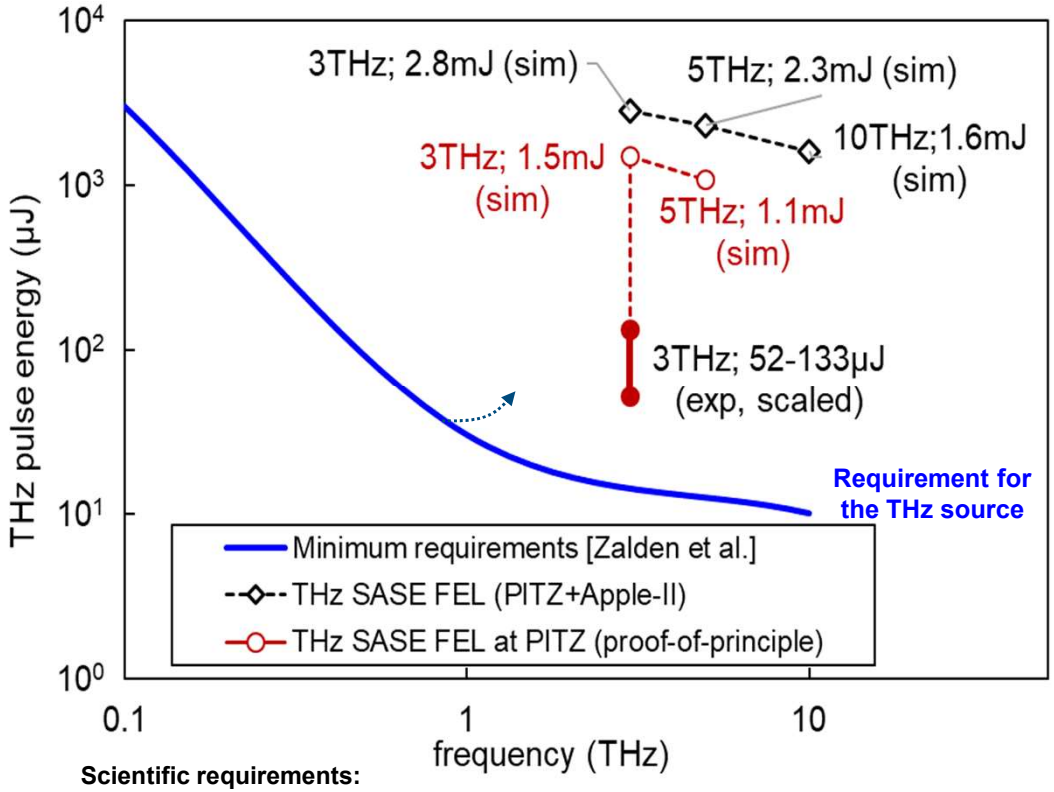
- Simulation of radiation process is very challenging (accurate initial noise modeling)
- Combine simulations and experimental results to predict possible performance (i.e. pulse energy)

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

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



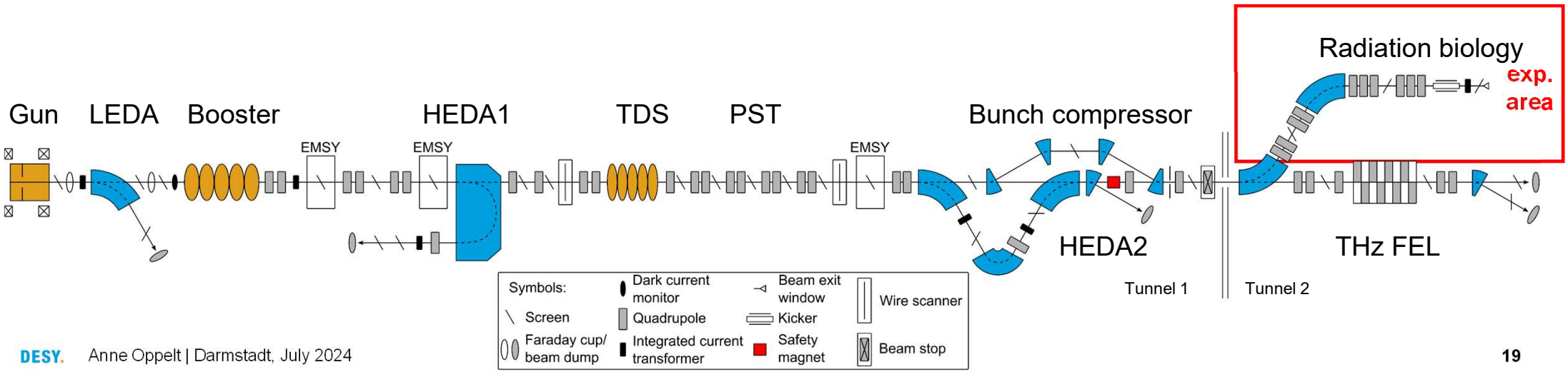




Scientific requirements:
[1] P. Zalden, et al., "Terahertz Science at European XFEL", XFEL.EU TN-2018-001-01.0
"...3 to 20 THz is the most difficult to cover by existing sources; at the same time, many vibrational resonances and relaxations in condensed matter occur at these frequencies."

Courtesy: M.Krasilnikov, X.Li

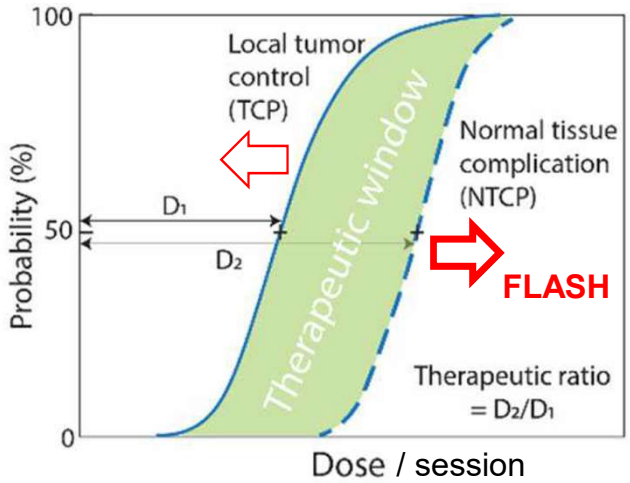
Radiation biology studies with FLASH*lab*@PITZ



Planned activities at FLASH*lab*@PITZ

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

- FLASH effect:
  - **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
- 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 will be installed in the PITZ tunnel extension

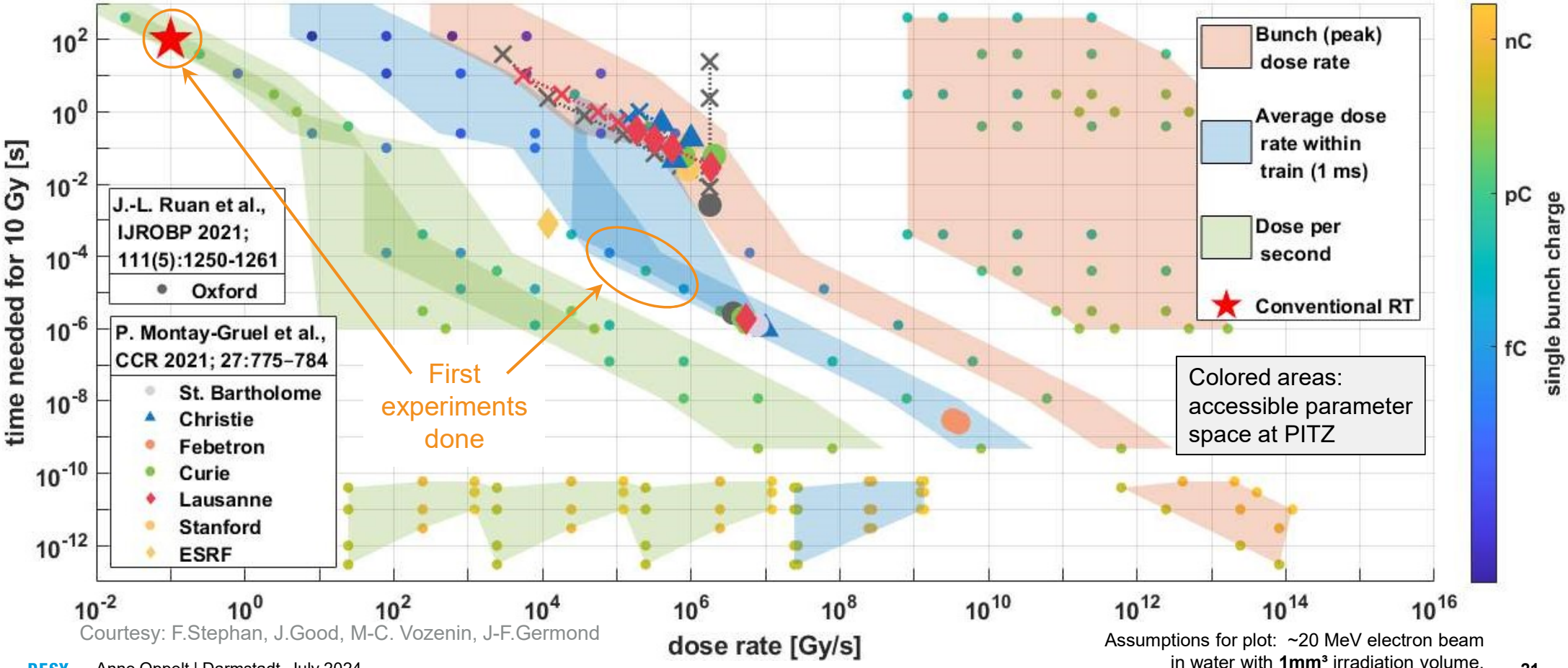


From M.R. Ashraf et al., Frontiers in Physics, 2020, doi: 10.3389/fphy.2020.00328

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



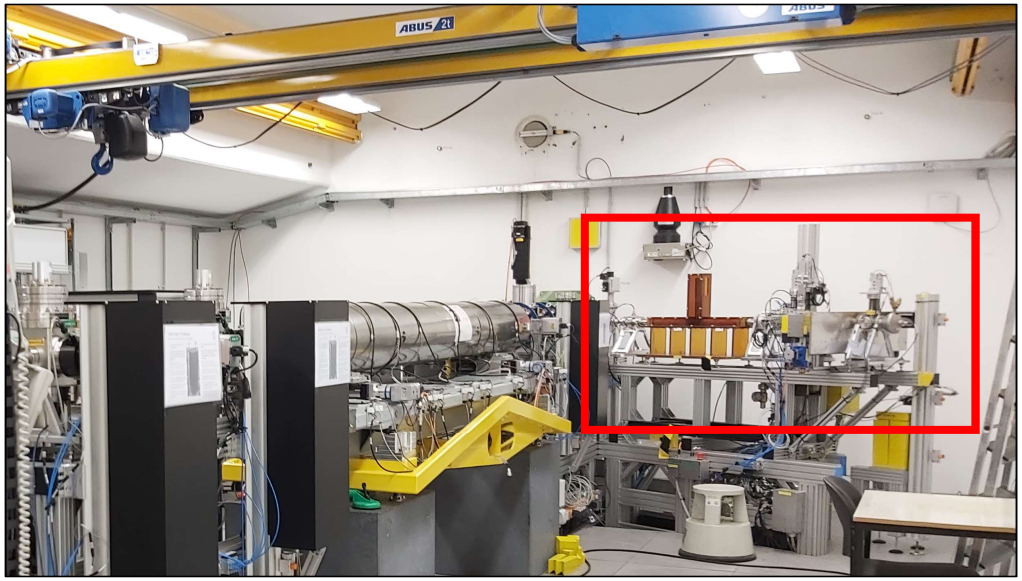
Courtesy: F.Stephan, J.Good, M-C. Vozenin, J-F.Germond

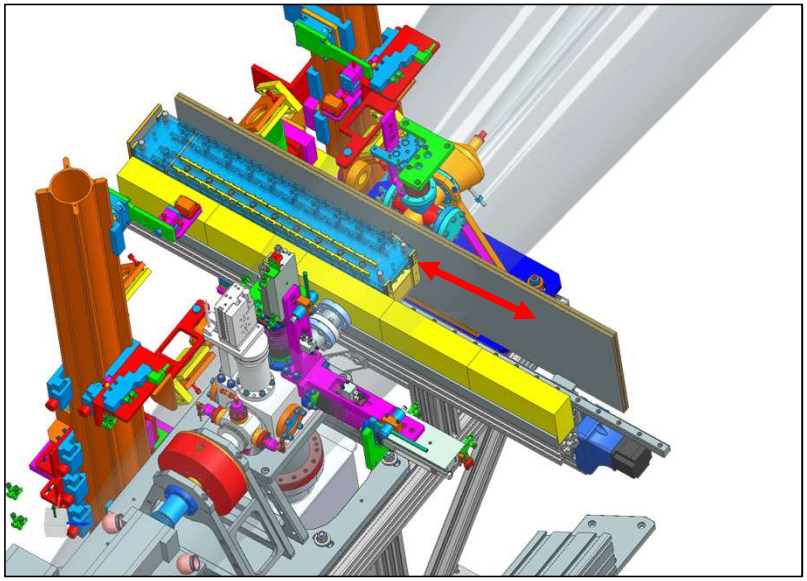
Assumptions for plot: ~20 MeV electron beam in water with **1mm³** irradiation volume.

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





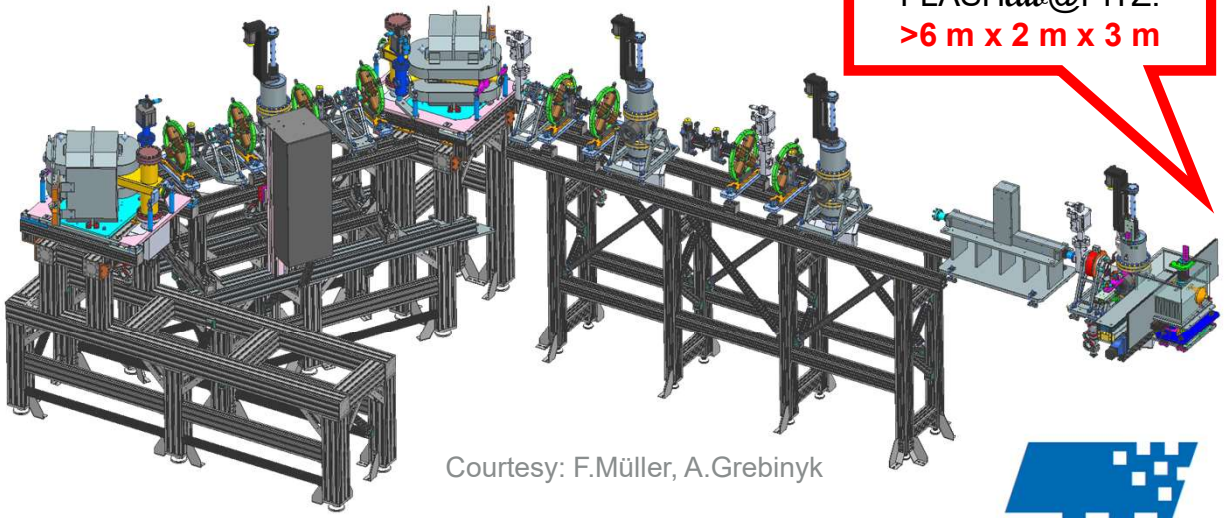
Courtesy: F.Müller, A.Grebinyk

New experimental beamline

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, …



Courtesy: F.Müller, A.Grebinyk

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

PITZ at this Meeting

Further presentations of ongoing research at PITZ

- **Namra Aftab** — 4D Transverse phase space characterization at PITZ via virtual pepper pot
  Poster and speed talk
  Session 2: Beam Diagnostics (4.7.2024, 16:10)
- **Sumaira Zeeshan** — Emittance Optimization studies with Photo-Injector Laser Pulse shaping for PITZ
  Poster and speed talk
  Session 4: Beam Dynamics (5.7.2024, 10:00)

Thank you for your attention!