FLASHLAB@PITZ: IRRADIATION EXPERIMENTS WITH HIGH DOSES AND DOSE RATES.

13th MT-ARD-ST3 meeting 2025,

Pre-Workshop "Medical applications"

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HELMHOLTZ

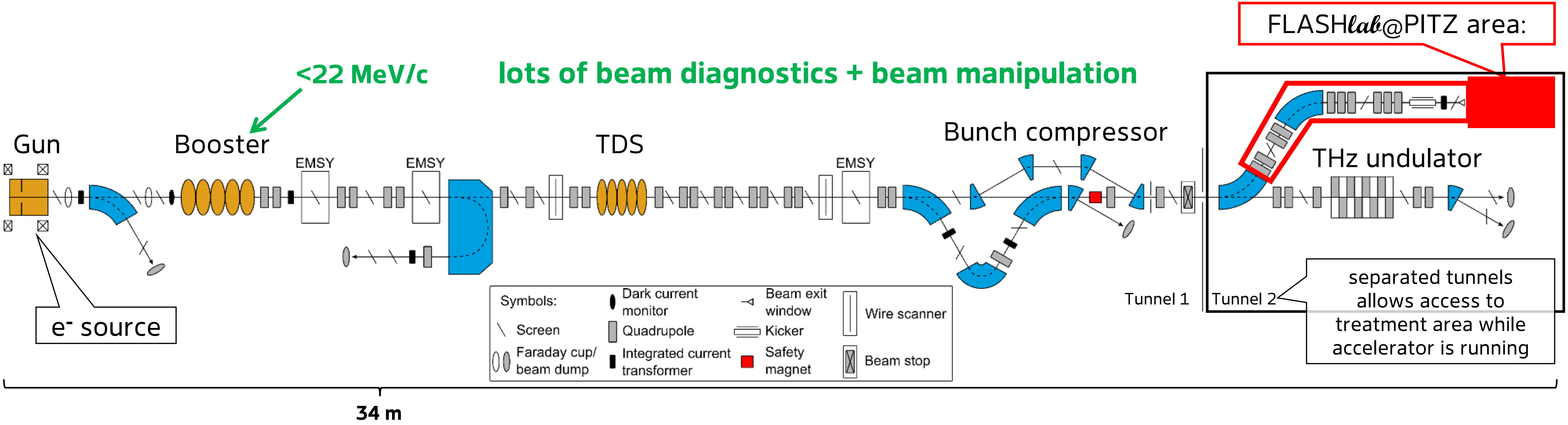
Experiments at FLASH*lab*@PITZ

A test bed infrastructure capable of Ultra-High Dose Rate (UHDR)

The **P**hoto **I**njector **T**est facility at DESY in **Z**euthen (**PITZ**) was+is used to **test** and **optimize** high brightness **electron sources** for Free-Electron-Laser **user facilities** (**FELs**) like the European XFEL in Hamburg

PITZ is conducting R&D and applications

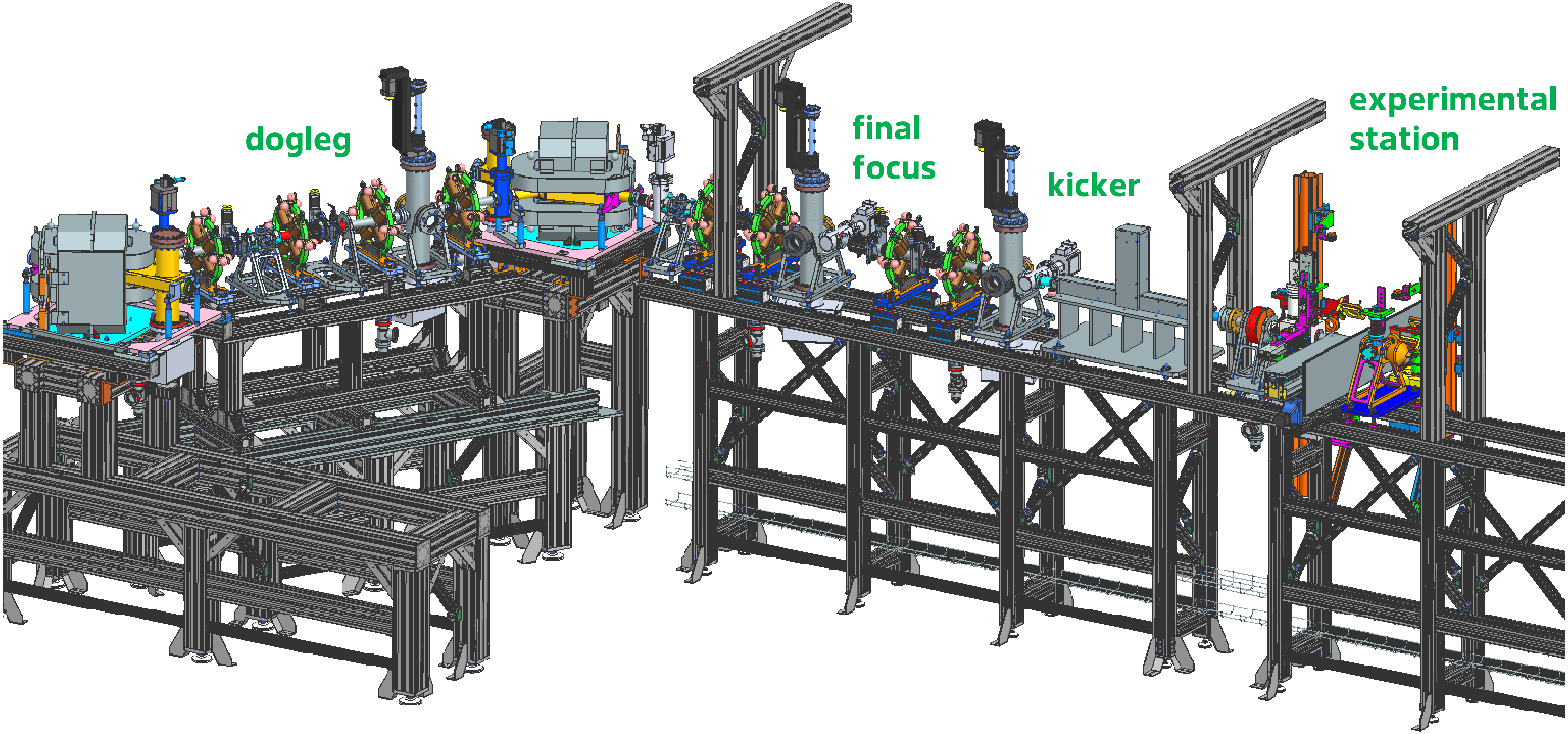
➔ **R&D on electron FLASH radiation therapy (FLASH*lab*@PITZ)**



Design of beamline as realized in 2025

Courtesy:
Frieder Müller

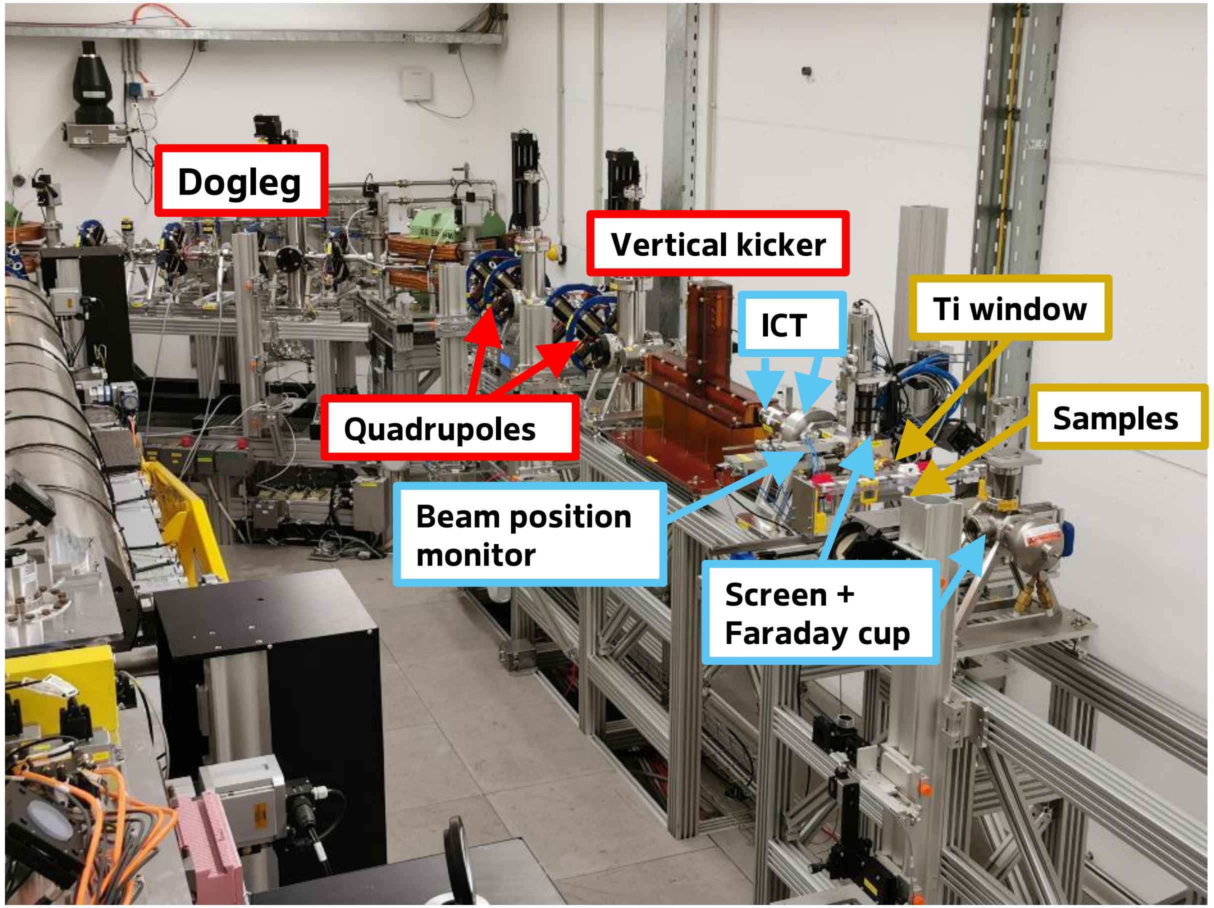
First experiments planned soon



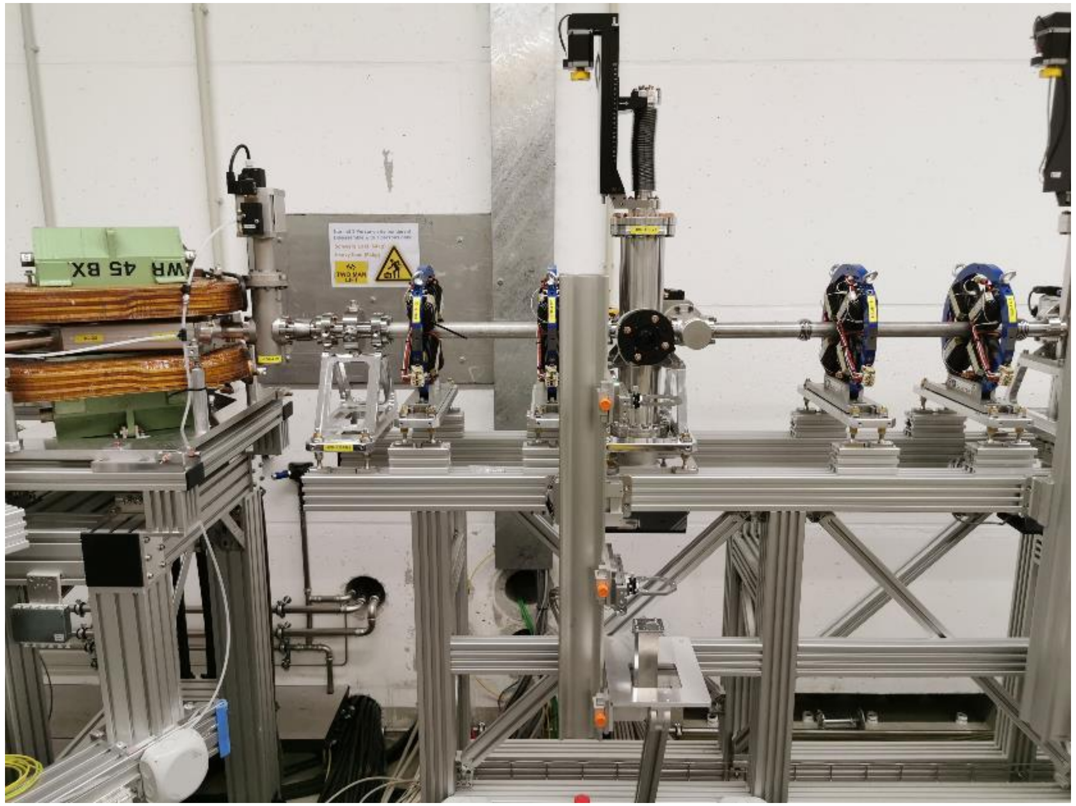
Status of construction

All components are installed; nominal vacuum in beam tube; cabling is almost ready

Beamline construction in tunnel 2 is finished for now (fast kicker will come later); commissioning has started

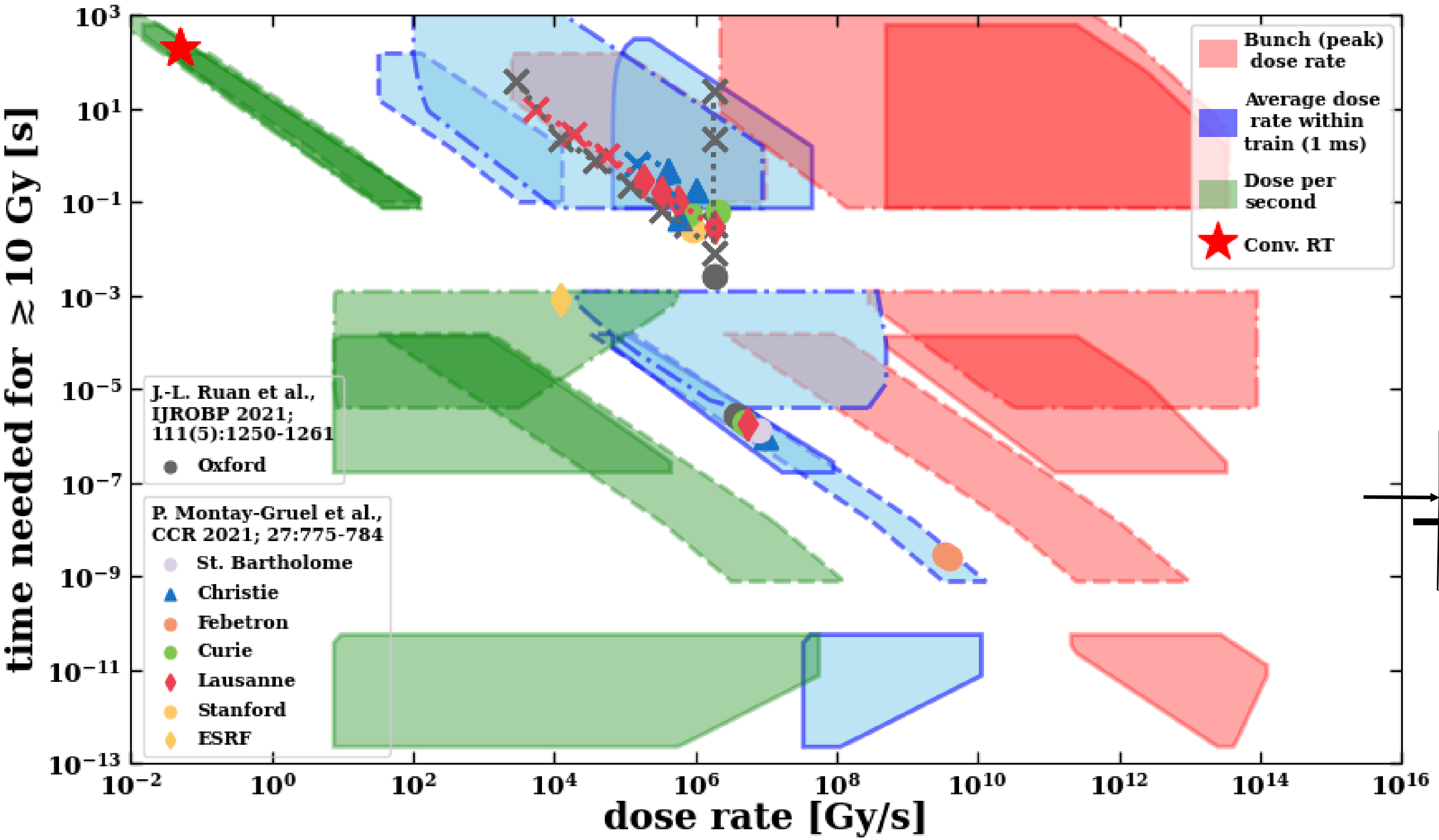


- 4 quads are used for beam focusing

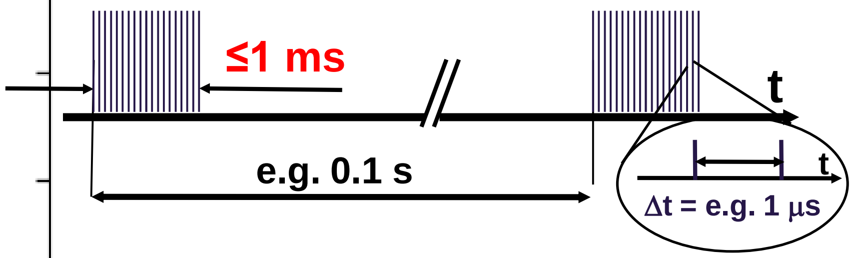


Dose parameter space

1 mm² for scattering beams and 0.5 - 1.5 mm RMS size for scanning beams



Time structure of electron bunches:



extremely flexible **pulse structure:**

ps → μs → ms → sec. + min

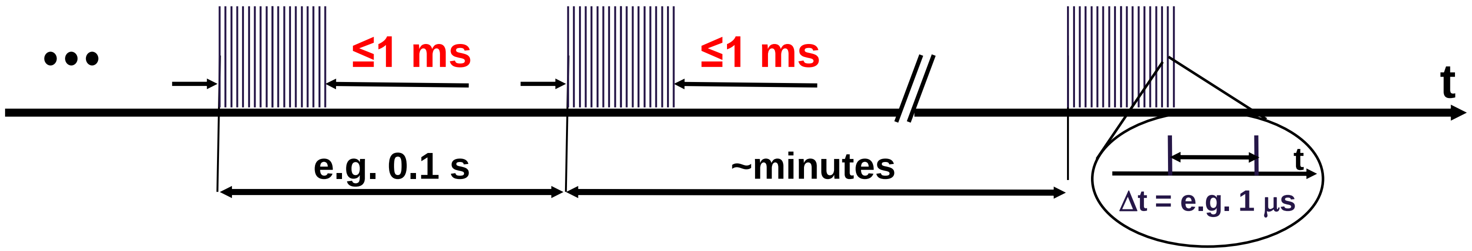
- separation of bunches to be chosen freely !

Challenges

1) Achieving high stability/reproducibility (beam orbit/bunch charge) with limited feedback

- Feature of FLASH irradiation: a single bunch train is used
  - Opposed to continuous operation at e.g. 10 Hz
- Goal: generate bunch train with identical bunches with controlled properties

Time structure of electron bunches:



- Procedure:
  - Beam tuning
  - Sample preparation
  - Irradiation

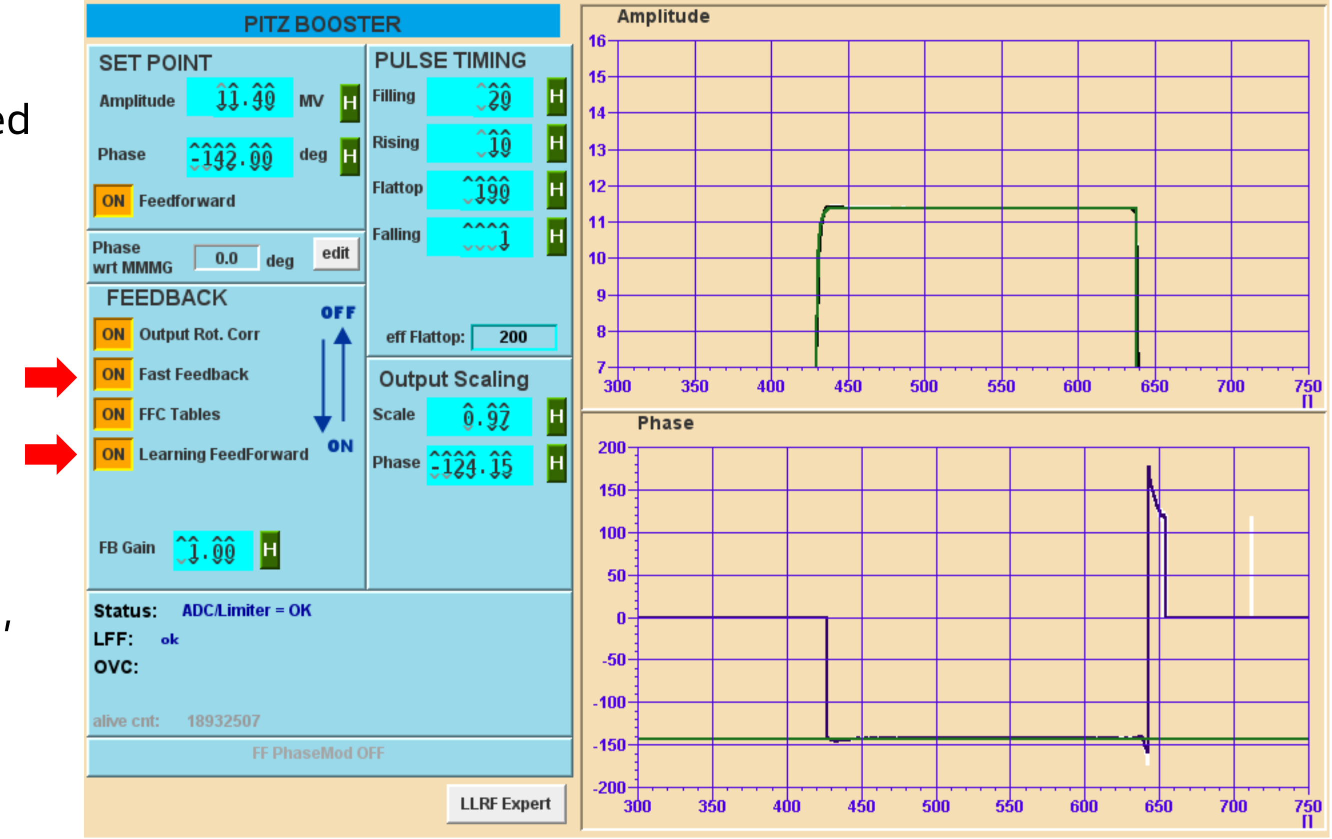
- Feedback loops (charge, orbit) only work with beam
  - Machine (laser, accelerator) has to run stably
  - Minimize time between beam tuning and irradiation
  - Option: kicker to dump beam during sample preparation
  - … [discussion]

Challenges

2) Beam loading

- Combination of high dose rate and high dose → lots of bunches with high charge (nC)
- Feature of FLASH irradiation: a single bunch train is used
  - Big challenge: LLRF
- Fast feedback: works within one RF pulse → ✓
- Learning feed forward
  - Looks at history over last 10+ seconds for additional stability; data is stored in tables
  - Ok, when tuning the beam; but then: switch off beam, insert sample, irradiate with single bunch train → 💣

Typical operation of PITZ booster



Challenges

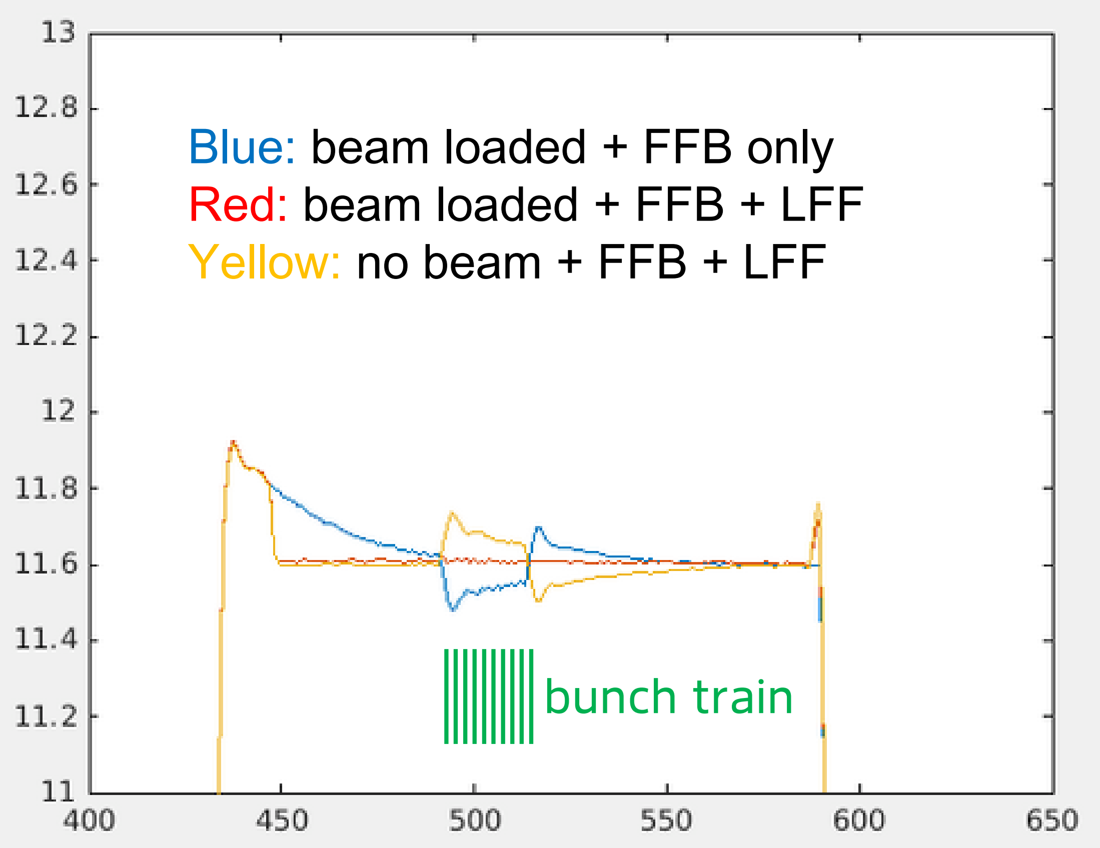
Courtesy:
Xiangkun Li

2) Beam loading

- Feature of FLASH irradiation: a single bunch train is used
  - Big challenge: LLRF
- Fast feedback (FFB) only: beam loading leads to acceleration gradient modulation
- Learning feed forward (LFF): beam loading is compensated for
  - But: it takes time

- Possible solution: Stop update of LFF table after tuning; use that data when switching on beam for irradiation
  - Compensation without beam (yellow) is inverted signal of beam loading without LFF (blue)

Measured beam loading effect (booster)



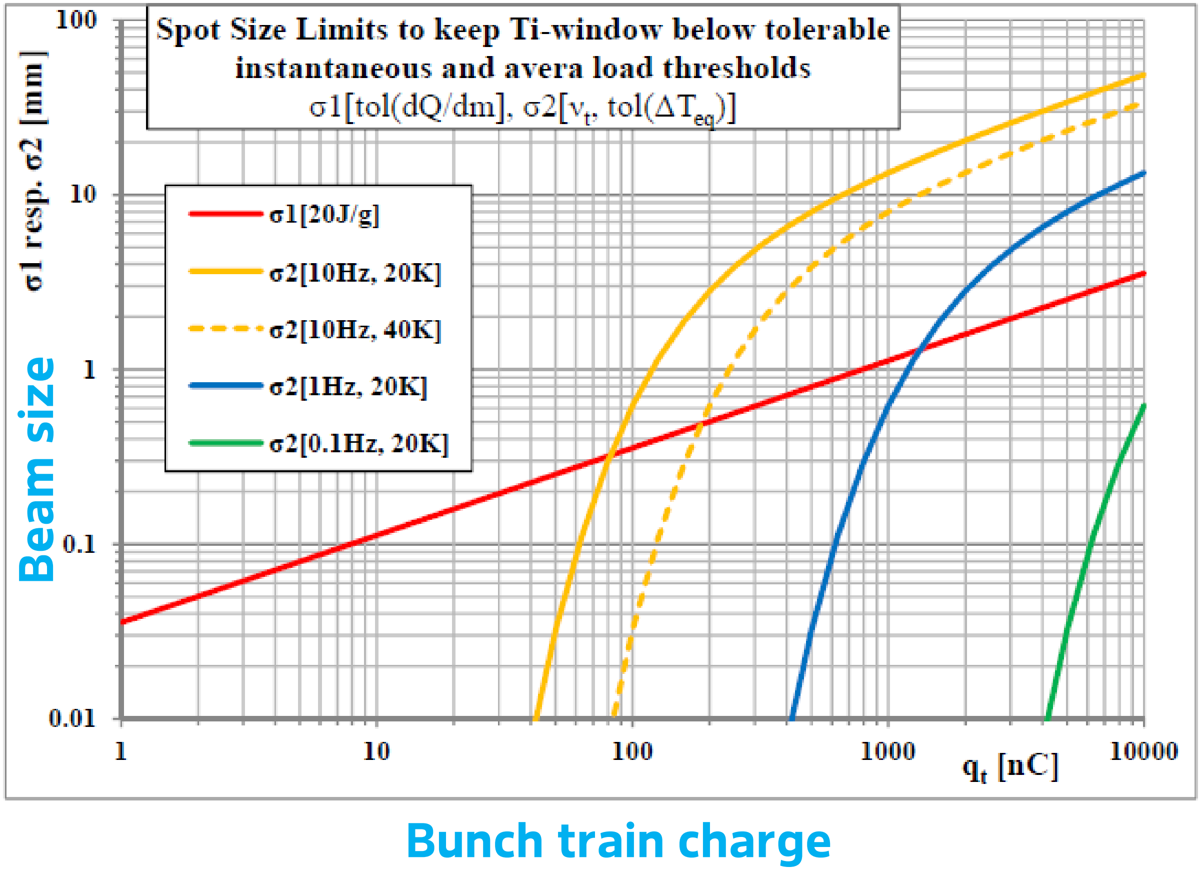
Challenges

Courtesy:
Michael Schmitz

3) High stress on the exit window (transition from vacuum to air)

- FLASH irradiation: high charge through the exit window in a short time
- Electrons are scattered in the window material → loss of energy → heat
  - Temperature too high → window damage
- Calculation of heat load:
  - Energy deposition by collision losses
  - Only radial thermal conduction from beam position to heat sink at circumference
  - σ1: heat induced mechanical stress
  - σ2: heating of window material
- Can be a severe restriction for scanning beams with kickers
- Alternative material: carbon (graphite, diamond) → high thermal conductivity

Operation limit DN40 mounted, 50 μm Ti window



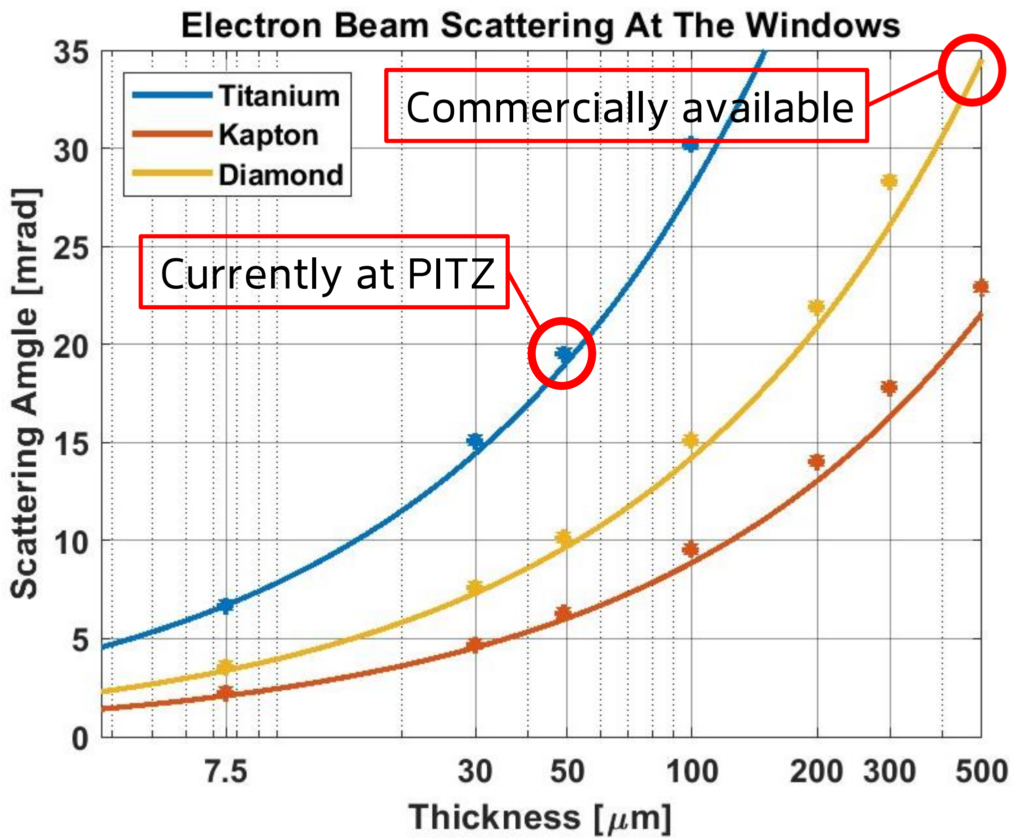
New possibility for exit window: CVD Diamond

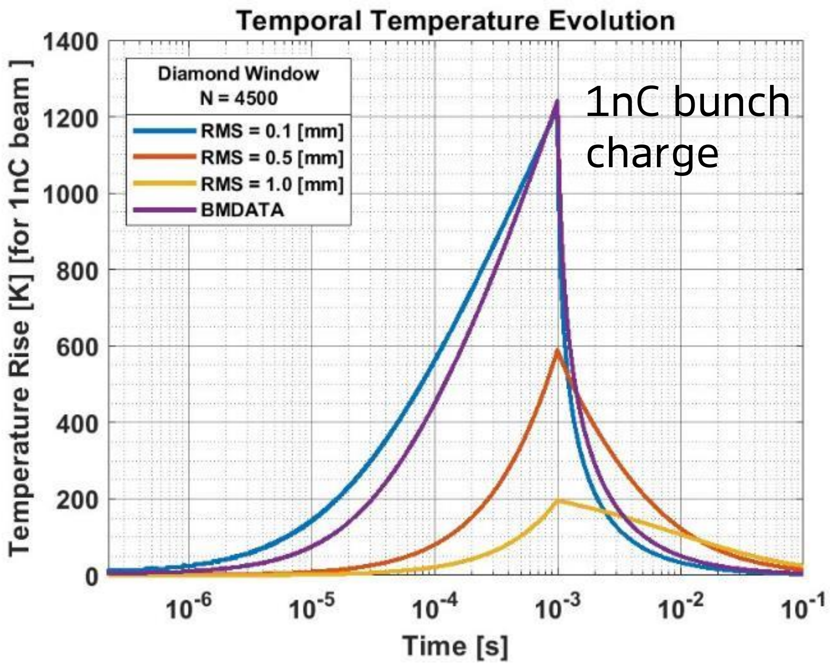
Courtesy:
Frieder Müller;
Zohrab
Amirkhanyan

Carbon materials (graphite, diamond): high thermal conductivity

Commercially available: vacuum ports made from CVD diamond

- Biggest advantage: much higher thermal conductivity compared to metals, e.g. titanium





- Much higher bunch charge allowed compared to Ti window. Examples for bunch trains with N bunches and rms size 0.1 mm:
  - N = 4500: 0.7 nC (diamond) ↔ 0.065 nC (Ti)
  - N = 500: >5 nC (diamond) ↔ 0.4 nC (Ti)

Summary

- FLASH*lab*@PITZ: new testbed for investigation of irradiations at ultra-high dose rates
  - Goal: investigate and optimize FLASH effect

- Huge available parameter range brings challenges:

1. Achieving high stability/reproducibility (beam orbit/bunch charge) with limited feedback
2. Beam loading
3. High stress on the exit window (transition from vacuum to air)