Steady State Microbunching in Storage Rings – Proof of Principle Results at MLS

Steady State Micro-Bunching Light Source Online Workshop, Dec 7-9, **2020, Tsinghua Uni**

Jörg Feikes, On behalf and using slides of the SSMB Collaboration

SSMB Collaboration

Tsinghua University, Beijing: Alex Chao, Xiujie Deng, Wenhui Huang, Lixin Yan**,** Chuanxiang Tang, Huan Wang, Zizheng Li, Yao Zhang, Zhilong Pan
Helmholtz-Zentrum Berlin: Jörg Feikes, Arnold Kruschinski, Ji Li, Aleksandr Matveenko, Yuriy Petenev, Markus Ries
Physikalisch-Technische Bundesanstalt (PTB): Arne Hoehl, Roman Klein
Shanghai Synchrotron Radiation Facility: Bocheng Jiang, Chao Feng, Xiaofan Wang, Changliang Li, Weishi Wan
Tsinghua University, Hsin-Chu: Hao-Wen Luo, Poshun Wu, Ci-Ling Pan, Make Ying

Recent conference reports by the collaboration

Joerg Feikes, VUV and EUV Metrology Workshop 2019, First experiment towards steady state micro bunching successfully performed at the Metrology Light Source
Changliang Li et al., IPAC19, Lattice design for the reversible SSMB
Zhilong Pan, FEL 2019, A Storage Ring Design for Steady-State Microbunching to Generate Coherent EUV Light Source
Chuanxiang Tang, IPAC2020, First experimental demonstration of the mechanism of steady-state microbunching
Xiujie Deng, EUVL2020, High-power EUV light source based on steady-state microbunching mechanism

Outline

- Idea and main result of the SSMB PoPI experiment
- Description of the experimental setup at the MLS lab in Berlin

-> storage ring, machine optics, general parameter set, laser setup, coherent detection system

- SSMB setup procedure
- Results
- Recent improvements of setup
- Future plans
- Summary

SSMB Collaboration

- An initial task force has been established at Tsinghua University to promote SSMB research with the goal of developing an SSMB storage ring.
- Three main tasks:
  1. Proof-of-principle (PoP) experiment
  2. Lattice design for SSMB ring[4-6]
  3. Resolve related technical issues

- C. Tang, et al., An Overview of the Progress on SSMB, in Proceedings of FLS18, Shanghai, China, 2018.
- A. Chao, et al., A Compact High-power Radiation Source Based on Steady-state Microbunching Mechanism, SLAC Technical Report No. SLAC-PUB-17241, 2018.
- T. Rui, et al., Strong Focusing Lattice Design for SSMB, in Proceedings of FLS18, Shanghai, China, 2018.
- Z. Pan, et al., A Storage Ring Design for Steady-state Microbunching to Generate Coherent EUV Light Source, in Proceedings of FEL19, Hamburg, Germany, 2019.
- C. Li, et al., Lattice design for the reversible SSMB, in Proceedings of IPAC19, Melbourne, Australia, 2019.


The First SSMB Collaboration Meeting at Tsinghua University, Beijing, 21st July, 2017

Proof-of-Principle experiments at MLS

A **PoP experiment** was succesfully performed at the Metrology Light Source, Berlin by a collaboration of **Tsinghua, HZB and PTB**.

Phase-I

- **Test of SSMB mechanism** in the steady-state isochronous environment of a stored electron beam.
- With very limited resources, use existing MLS, and an existing available single-shot laser, **Start Feb 2019**
- demonstrated SSMB mechanism at MLS, **May 2019**
- quadratic dependency of coherent signal on single bunch current confirmed **August 2019**

Experiment is highly demanding:

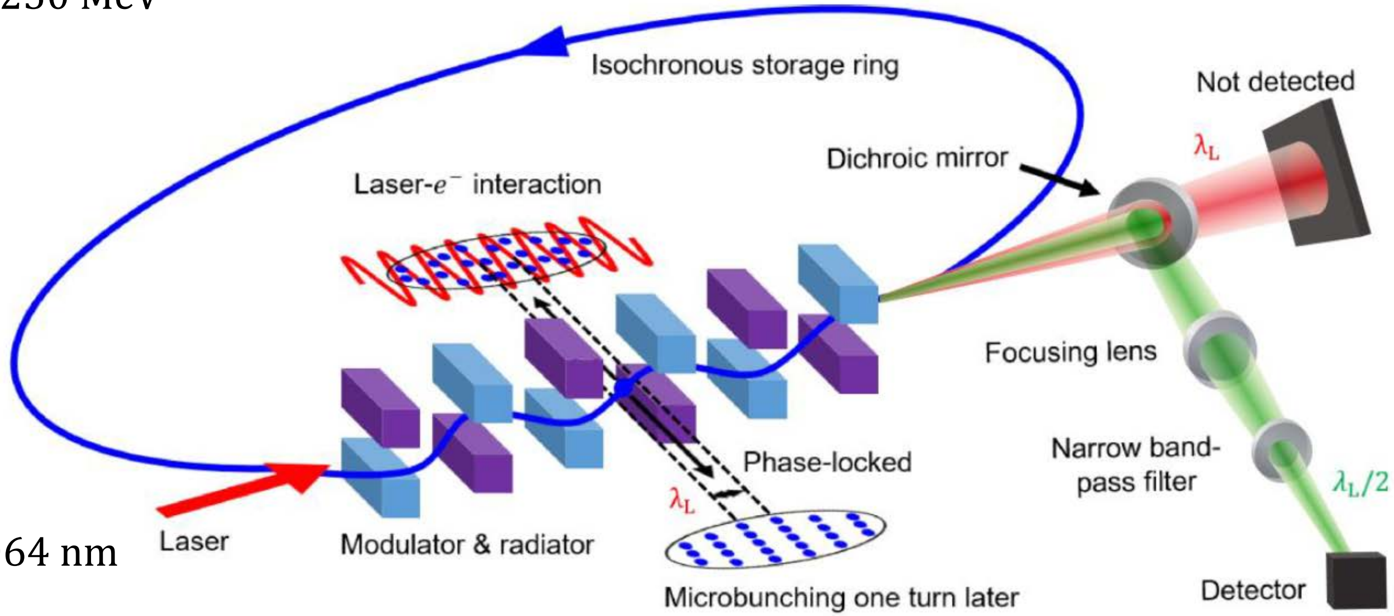
- very **high precision setting** needed for many machine parameter simultaneously
- full understanding of all relevant micro structure **smearing effects** is essential
- some parameters cannot be measured to the needed accuracy –> **multi-dimensional scans** needed
- stability of the **beam laser system** (overlap, laser jitter) critical !
- **unexpected physical effects** appeared (impact of non-linearities, alpha bucket state)

SSMB PoP Phase I[*]

Electron beam is stored in an isochronous configuration at MLS. The beam is modulated by a single-shot laser. The beam makes one turn and returns to the modulator, which now serves as the radiator.

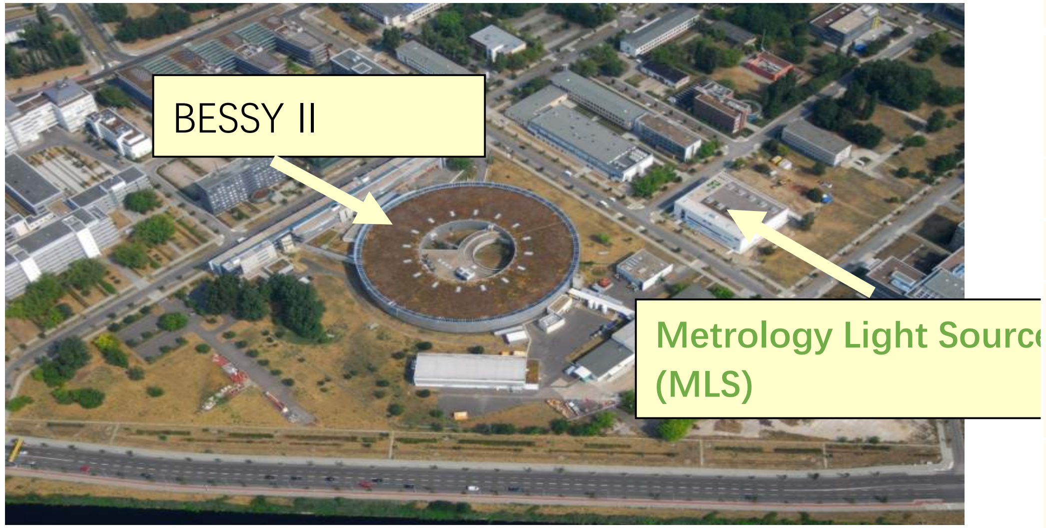
$C = 48\,\mathrm{m}$ $\alpha \approx -2 \times 10^{-5}$ $E = 250\,\mathrm{MeV}$

$\lambda = 1064\,\mathrm{nm}$



[*]X. Deng, A. Chao, J. Feikes, A. Hoehl, W. Huang, R. Klein, A. Kruschinski, J. Li, A. Matveenko, Y. Petenev, M. Ries, C. Tang and L. Yan, Experimental Demonstration of the Mechanism of Steady-state Microbunching, accepted for publishing by Natur

The Metrology Light Source

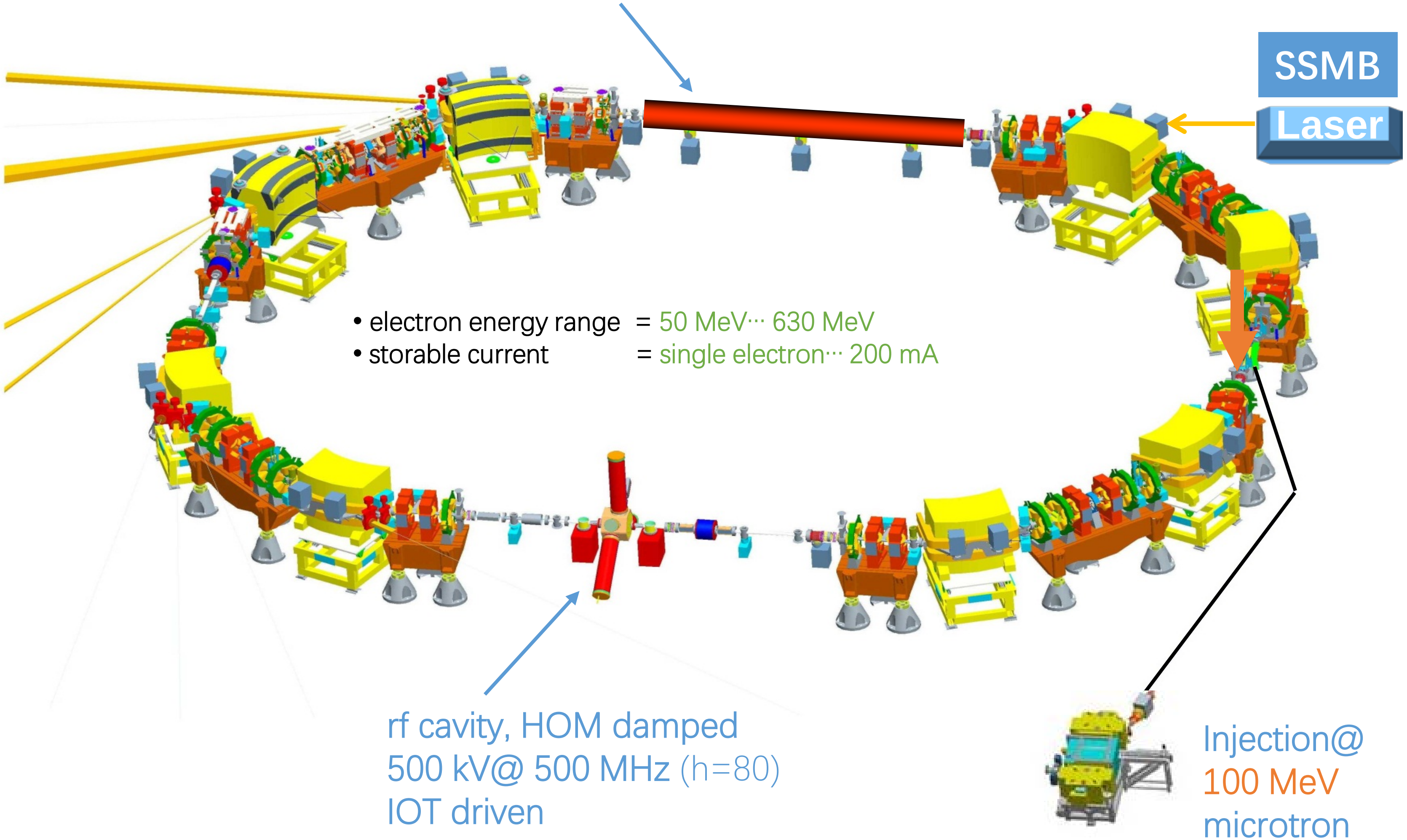


located south of Berlin, Germany

Circumference	48 m
Revolution frequency	f_{rev} = 6.25 MHz T_{rev} = 160 ns
Injection Energy	105 MeV
Operational Energy	50 MeV to 630 MeV
Beam Current	1 pA (1 e-) to 200 mA
Momentum Compaction Factor	$-5\text{x}10^{-2} < \alpha < 5\text{x}10^{-2}$
emittances at 630 MeV	25nmrad (low emittance) 100nmrad (standard user)
Typical lifetimes in different operation modes	Standard 6h @150mA 30h @1pA (1 e-) Low emit. 2h @150mA Low Alpha 10h @150mA

owner and main user: **P**hysikalisch-**T**echnische **B**undesanstalt (PTB)
operated by „BESSYII“-staff (Helmhotz-Zentrum-Berlin)

MLS - the storage ring



U125 undulator

SSMB

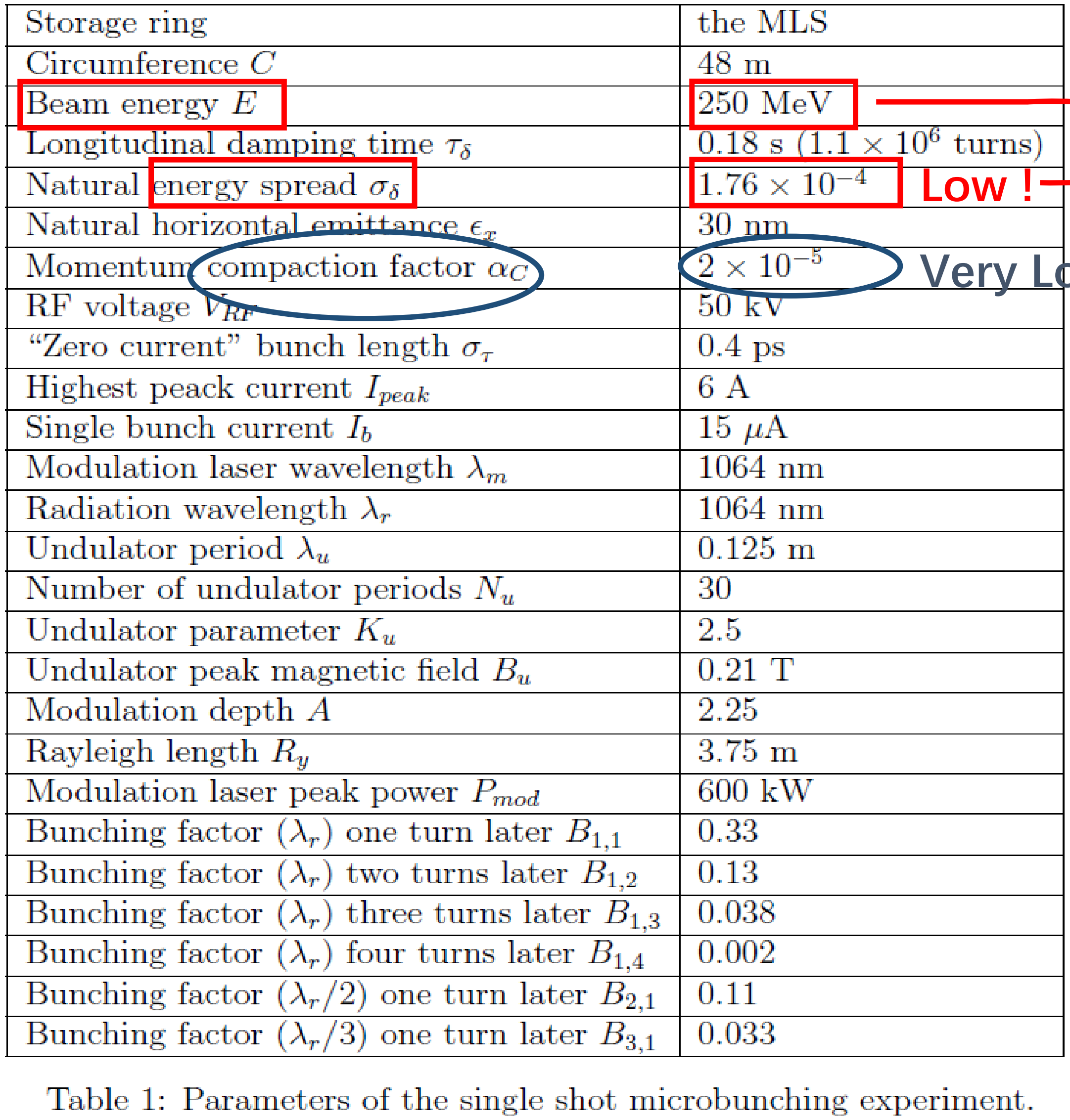
Laser

- electron energy range = 50 MeV··· 630 MeV
- storable current = single electron··· 200 mA

rf cavity, HOM damped
500 kV@ 500 MHz (h=80)
IOT driven

Injection@
100 MeV
microtron

Parameter setting for SSMB state as defined by Deng Xiujie



Storage ring	the MLS
Circumference C	48 m
Beam energy E	250 MeV
Longitudinal damping time τ_δ	0.18 s (1.1×10^6 turns)
Natural energy spread σ_δ	1.76×10^{-4}
Natural horizontal emittance ϵ_x	30 nm
Momentum compaction factor α_C	2×10^{-5}
RF voltage V_{RF}	50 kV
“Zero current” bunch length σ_τ	0.4 ps
Highest peack current I_{peak}	6 A
Single bunch current I_b	15 μA
Modulation laser wavelength λ_m	1064 nm
Radiation wavelength λ_r	1064 nm
Undulator period λ_u	0.125 m
Number of undulator periods N_u	30
Undulator parameter K_u	2.5
Undulator peak magnetic field B_u	0.21 T
Modulation depth A	2.25
Rayleigh length R_y	3.75 m
Modulation laser peak power P_{mod}	600 kW
Bunching factor (λ_r) one turn later $B_{1,1}$	0.33
Bunching factor (λ_r) two turns later $B_{1,2}$	0.13
Bunching factor (λ_r) three turns later $B_{1,3}$	0.038
Bunching factor (λ_r) four turns later $B_{1,4}$	0.002
Bunching factor ($\lambda_r/2$) one turn later $B_{2,1}$	0.11
Bunching factor ($\lambda_r/3$) one turn later $B_{3,1}$	0.033

Table 1: Parameters of the single shot microbunching experiment.

Low !

Very Low !

250 MEV NEGATIVE LOW ALPHA STATE (LOCO MEASUREMENT)

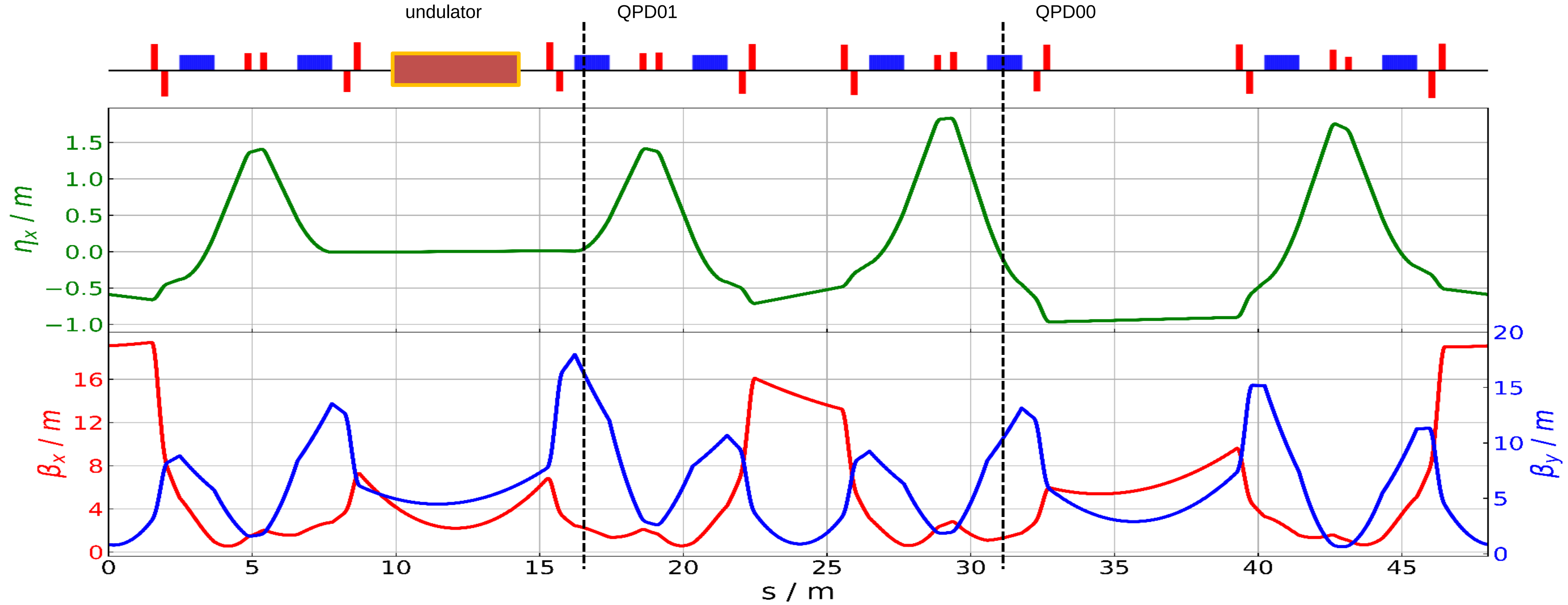
Emittance= 43.9 nm
σ_e=1.73E-4

Undulator: s =12 m
β_x = 2.21 m
β_y = 4.55 m
η_x = 0.0013 m
η'_x = 0.003
alpha0= -2E-5

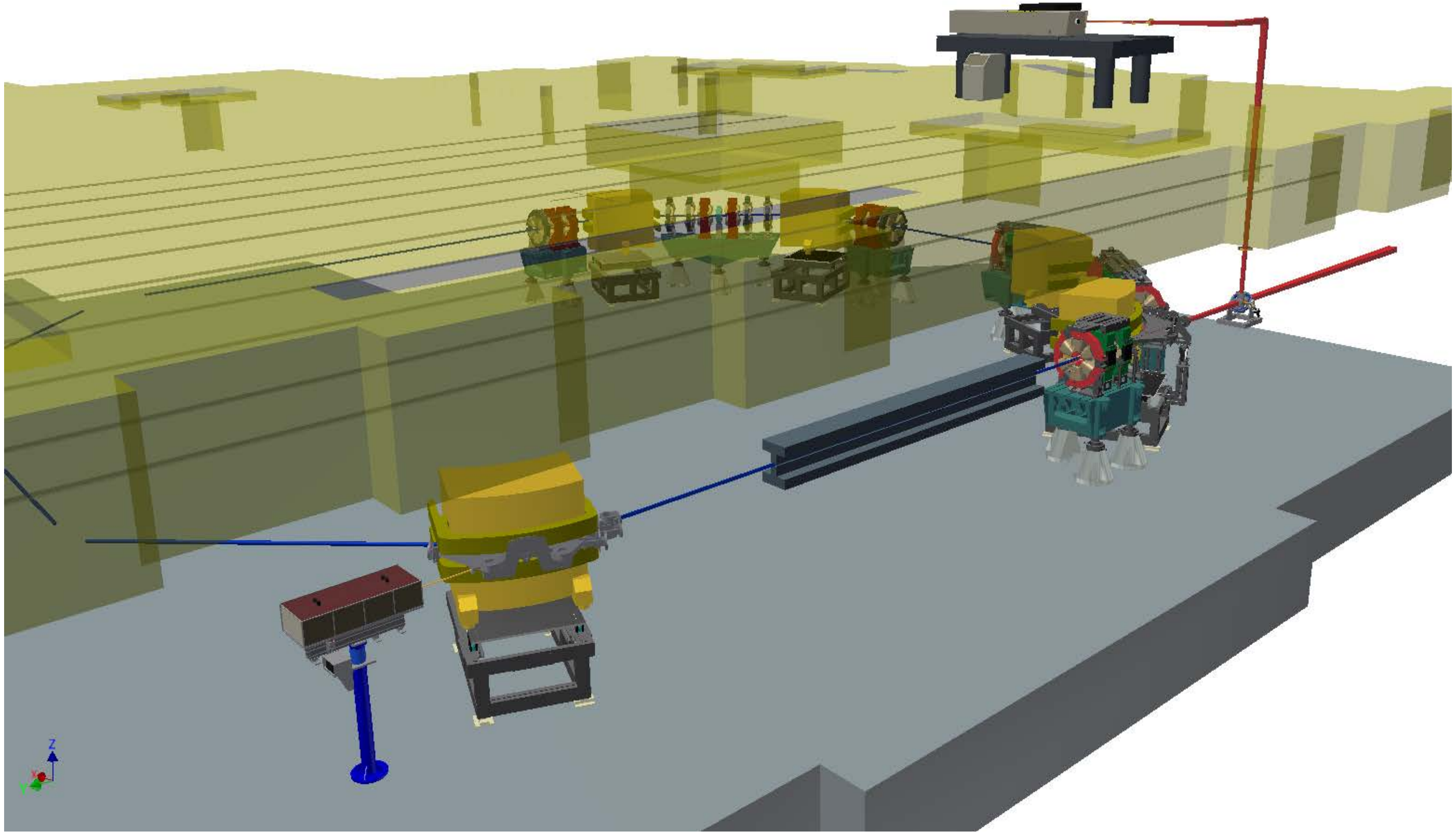
QPD01: s =16.525 m
β_x = 2.26 m
β_y = 16.36 m
η_x = 0.036 m
η'_x = 0.19

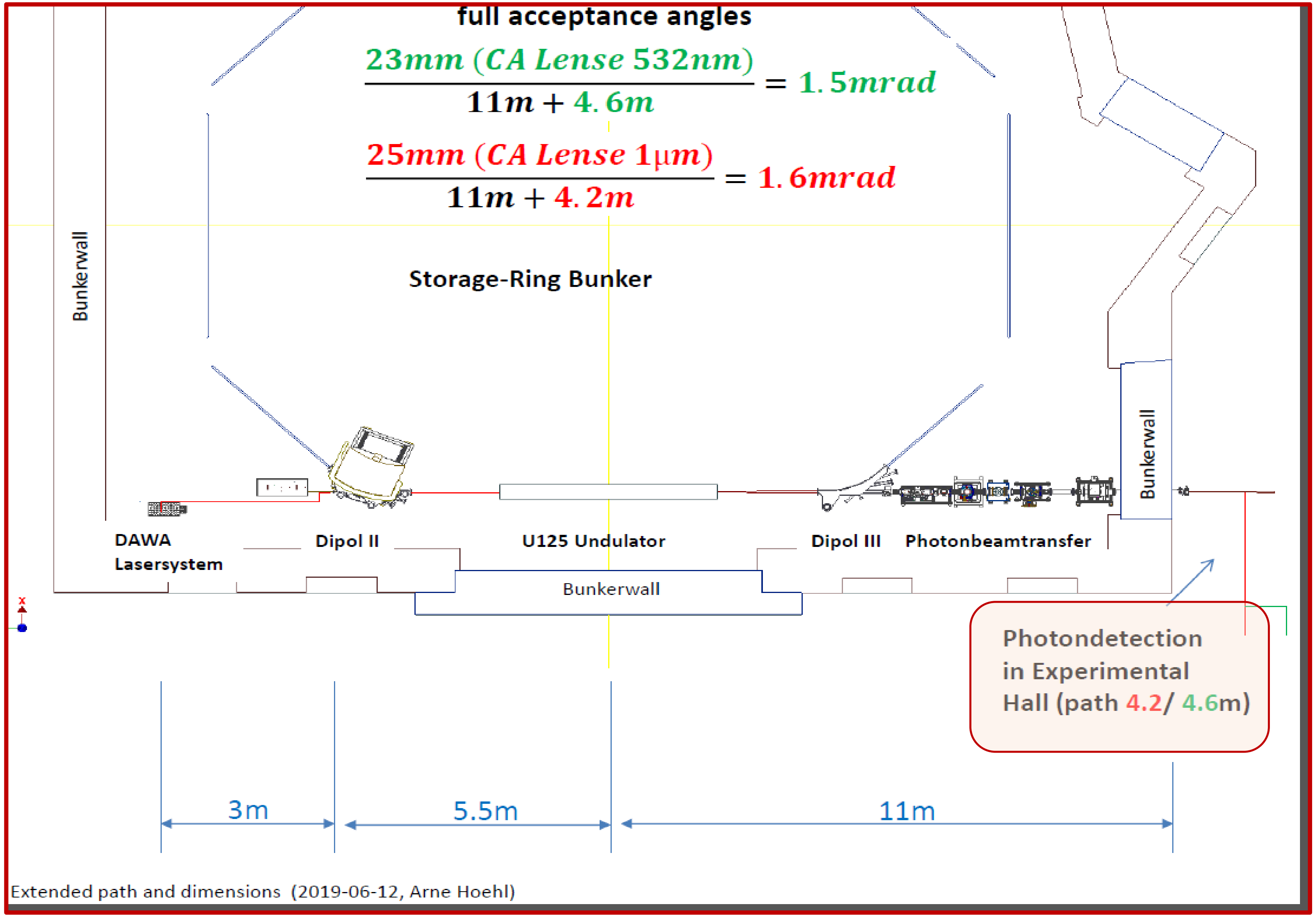
„QPD00, QPD01“ = beam imaging systems

QPD01: s = 31.175 m
β_x = 1.34 m
β_y = 10.61 m
η_x = -0.15 m
η'_x = -0.74



established optical path for Compton Back Scattering measurements used for an improvised SSMB setup





full acceptance angles

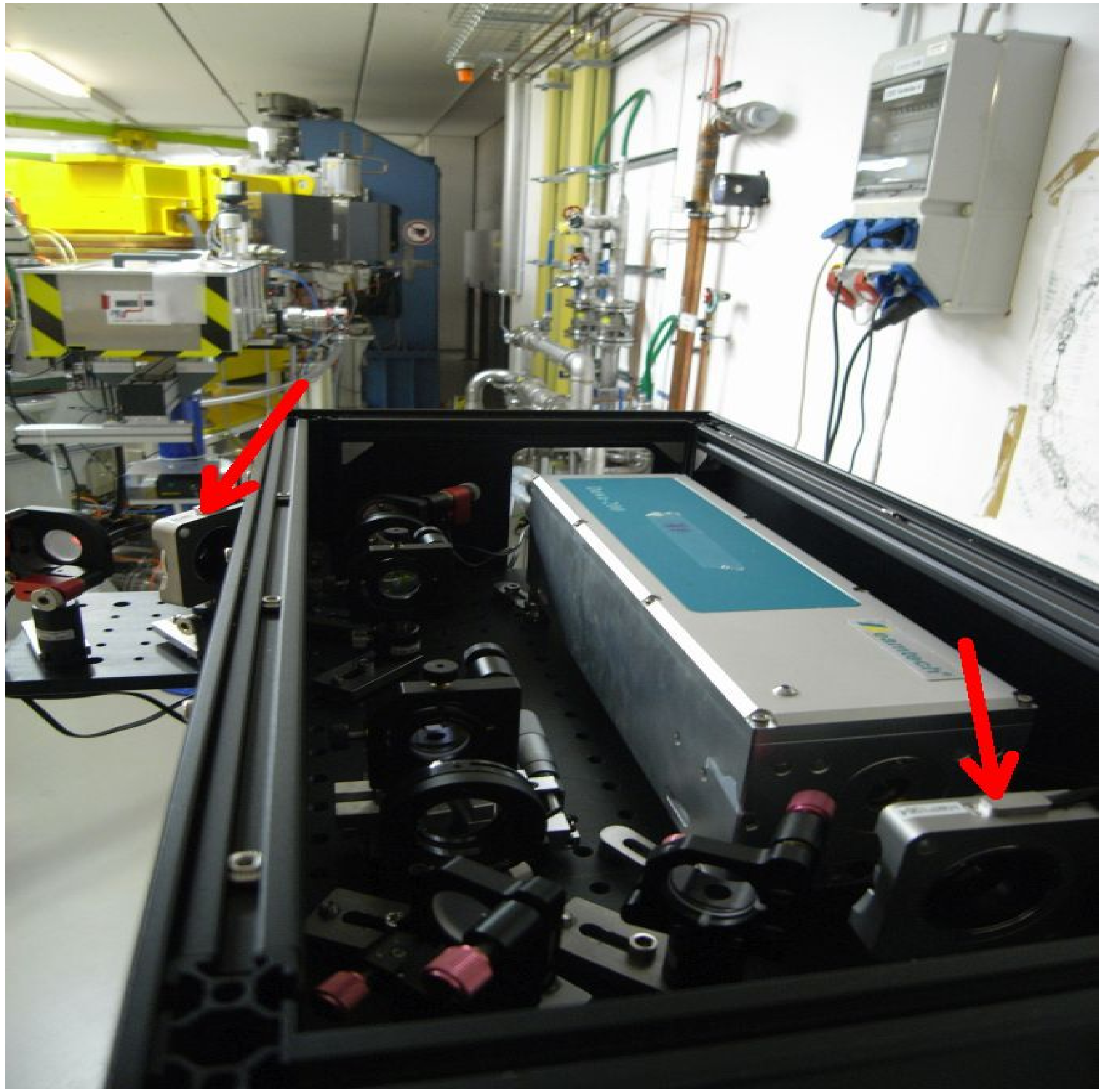
$$\frac{23mm\ (CA\ Lense\ 532nm)}{11m + 4.6m} = 1.5mrad$$

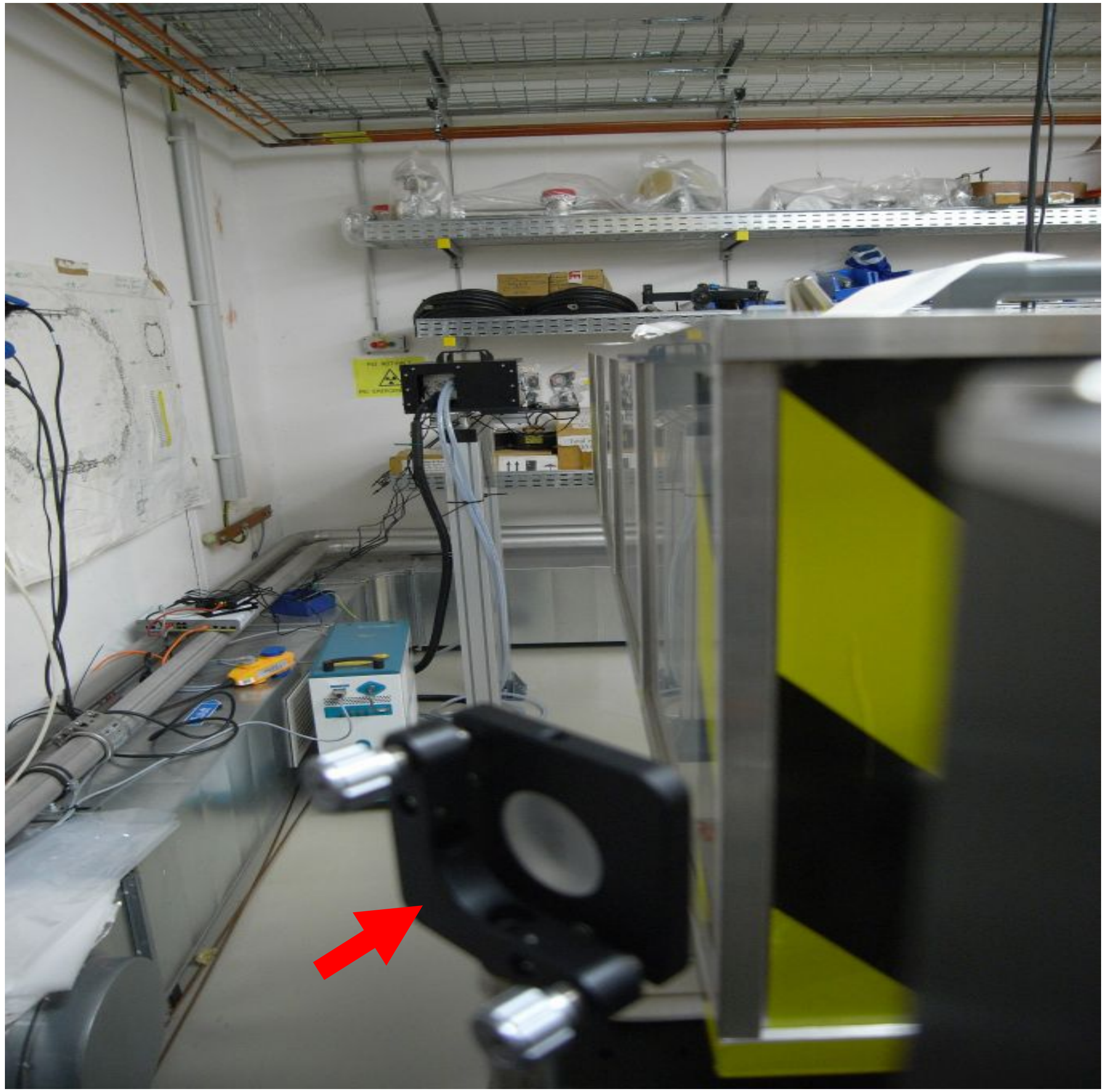
$$\frac{25mm\ (CA\ Lense\ 1\mu m)}{11m + 4.2m} = 1.6mrad$$

Photondetection in Experimental Hall (path 4.2/ 4.6m)

Extended path and dimensions (2019-06-12, Arne Hoehl)

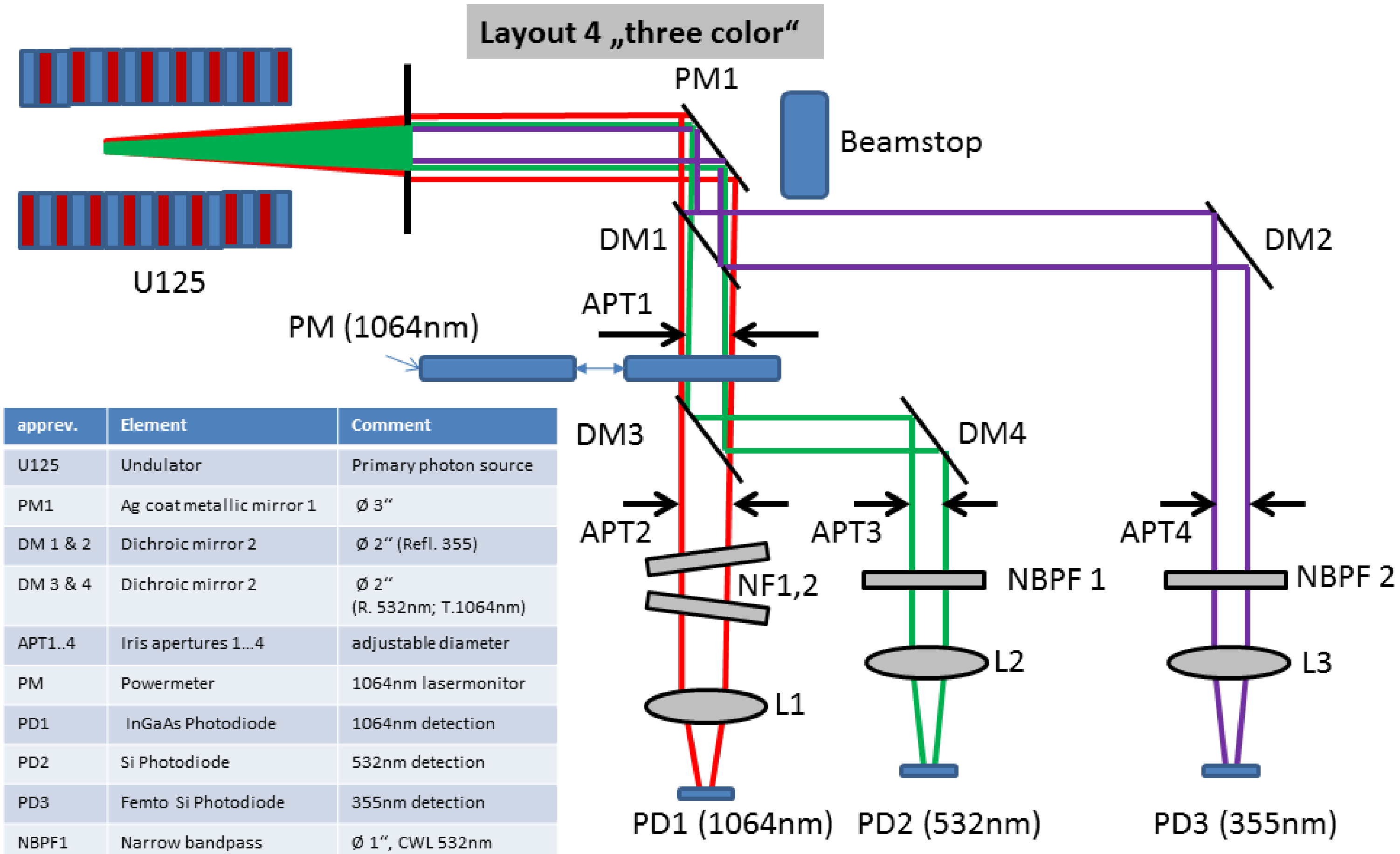
Laser and laser beam path inside MLS bunker





The coherent radiation detection setup

To reduce impact of laser stray light -> **signal detection on higher harmonics implemented**



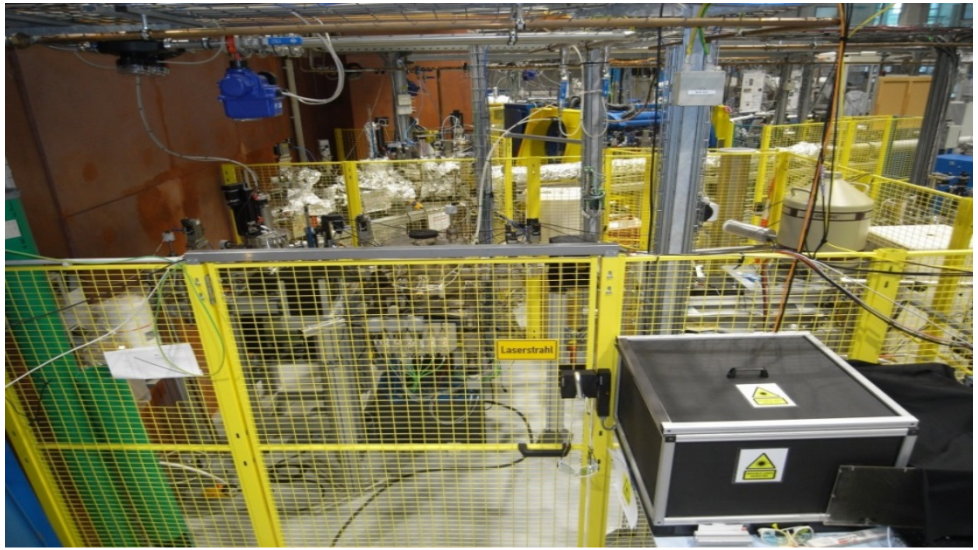
apprev.	Element	Comment
U125	Undulator	Primary photon source
PM1	Ag coat metallic mirror 1	Ø 3“
DM 1 & 2	Dichroic mirror 2	Ø 2“ (Refl. 355)
DM 3 & 4	Dichroic mirror 2	Ø 2“ (R. 532nm; T.1064nm)
APT1..4	Iris apertures 1…4	adjustable diameter
PM	Powermeter	1064nm lasermonitor
PD1	InGaAs Photodiode	1064nm detection
PD2	Si Photodiode	532nm detection
PD3	Femto Si Photodiode	355nm detection
NBPF1	Narrow bandpass	Ø 1“, CWL 532nm
NBPF2	Narrow bandpass	Ø 1“, CWL 354.7nm
NF1,2	Notchfilter 1	Ø 1“, CWL 1064nm
L1, L2, L3	Lense 1,2,3 (AR Coated)	Ø 1“, f=50mm or 75mm
NF1,2	Notchfilter 1	Ø 1“, 532nm reflection

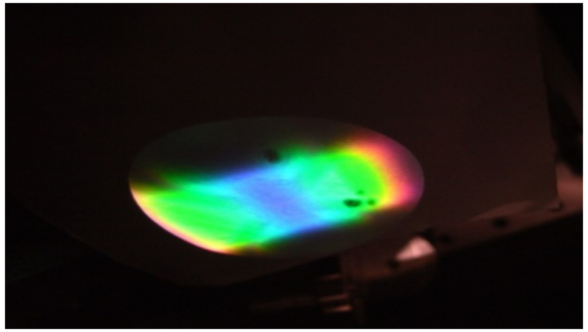
1064nm (Laser and Undulatorradiation)

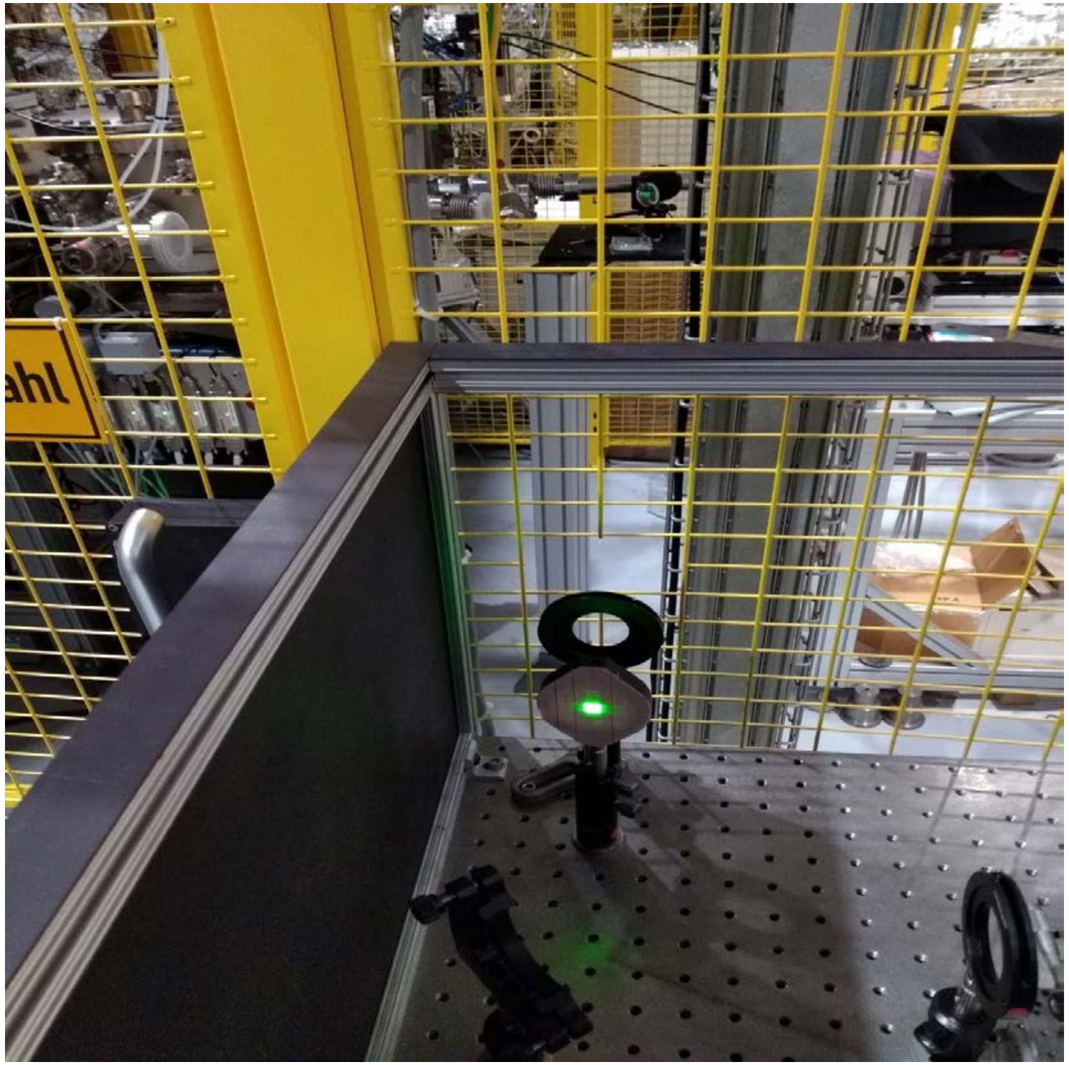
532nm 2nd harmonic SSMB signal

355nm 3rd harmonic SSMB signal

Detection area in the MLS experimental hall

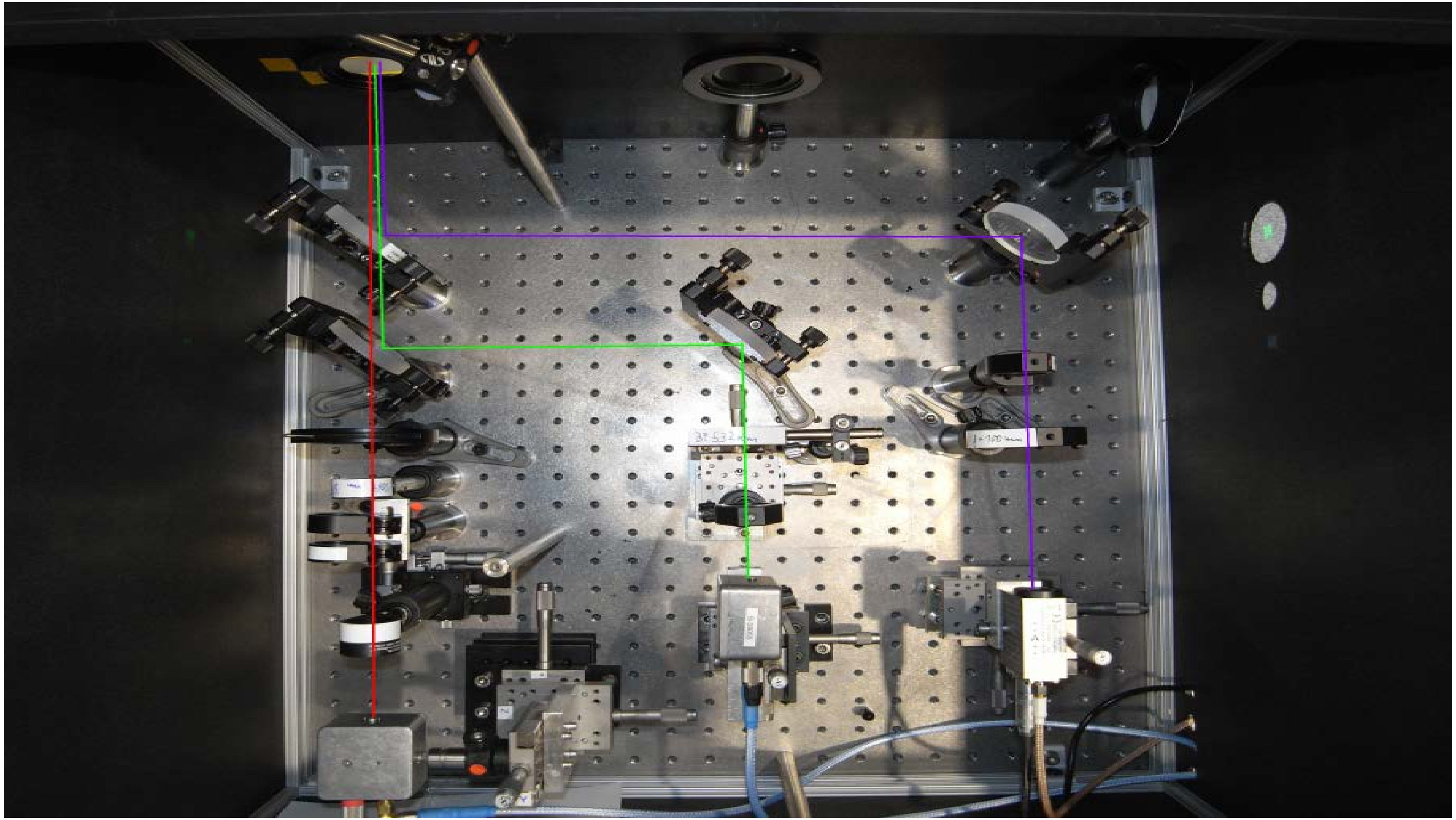






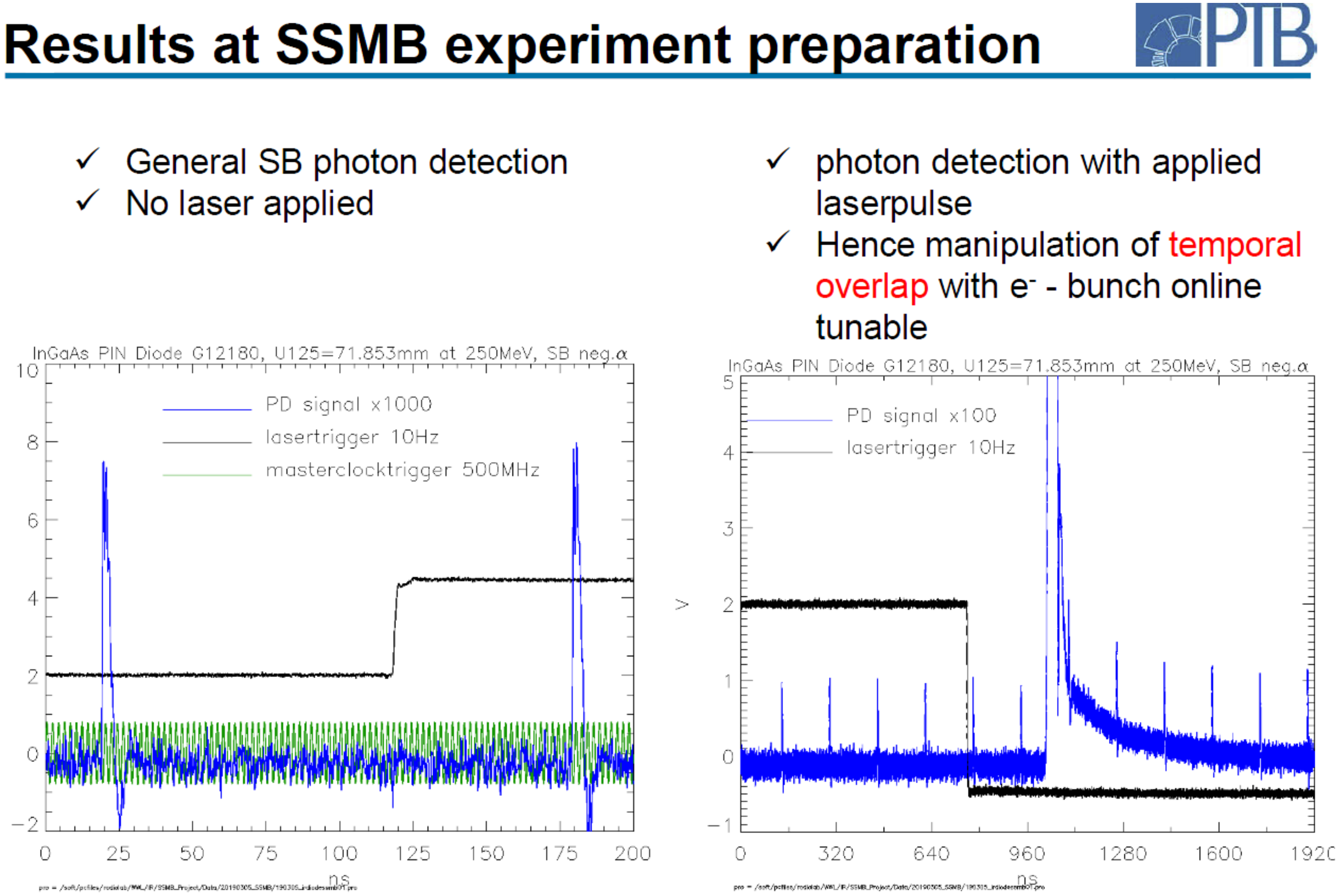
Lixin+Arne

The detection box



coherent detection only possible at 532nm (second harmonic)

-> Laser induces **strong saturation** and **damage** of photo diodes used for coherent light detection
-> due to the strong impact of **stray light** diode even 532nm signal disturbed due to **saturation effects**

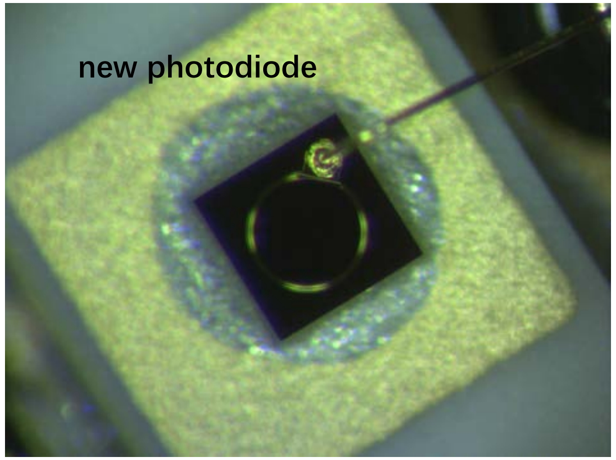


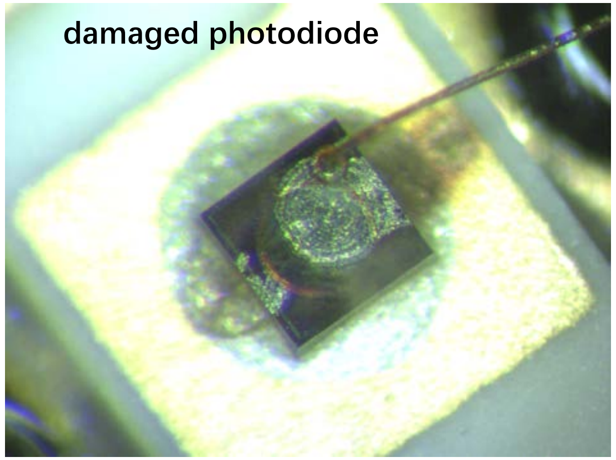
Results at SSMB experiment preparation

- ✓ General SB photon detection
- ✓ No laser applied

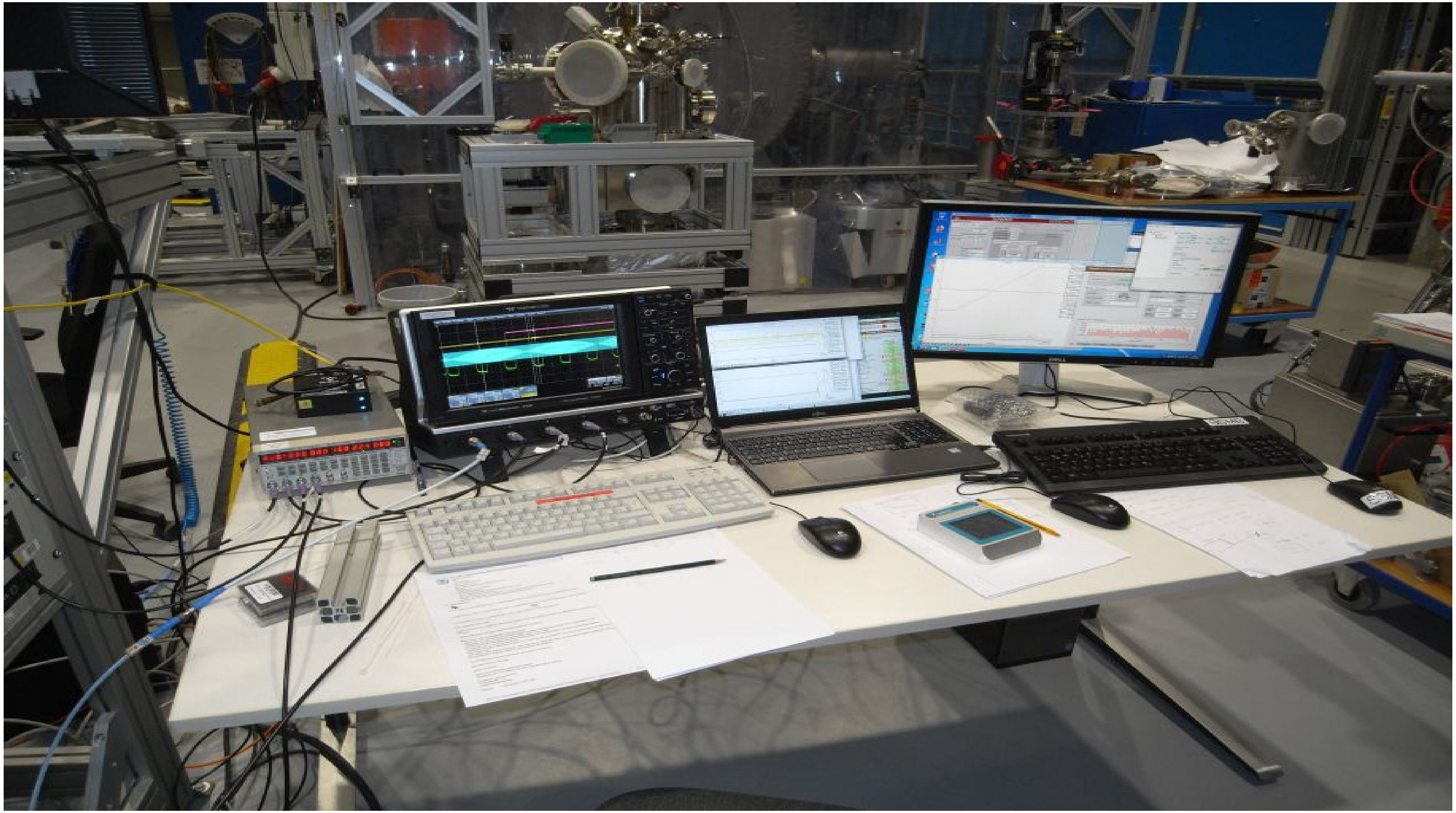
- ✓ photon detection with applied laserpulse
- ✓ Hence manipulation of temporal overlap with e^- - bunch online tunable

Signal at 532nm





Improvised SSMB control room located in the MLS experimental hall



Setup Procedure

- Switch MLS to **negative alpha Mode**, inject 40mA in N=80 bunches at **105 MeV**, ramp up to **630MeV** and then ramp down to a special **ramp optic** at **250MeV** with high **dispersion at undulator** (whole procedure ~1h)

- „Bunch cleaning“ using multi bunch feedback to reduce number of bunches to N=20

- Close undulator to desired gap

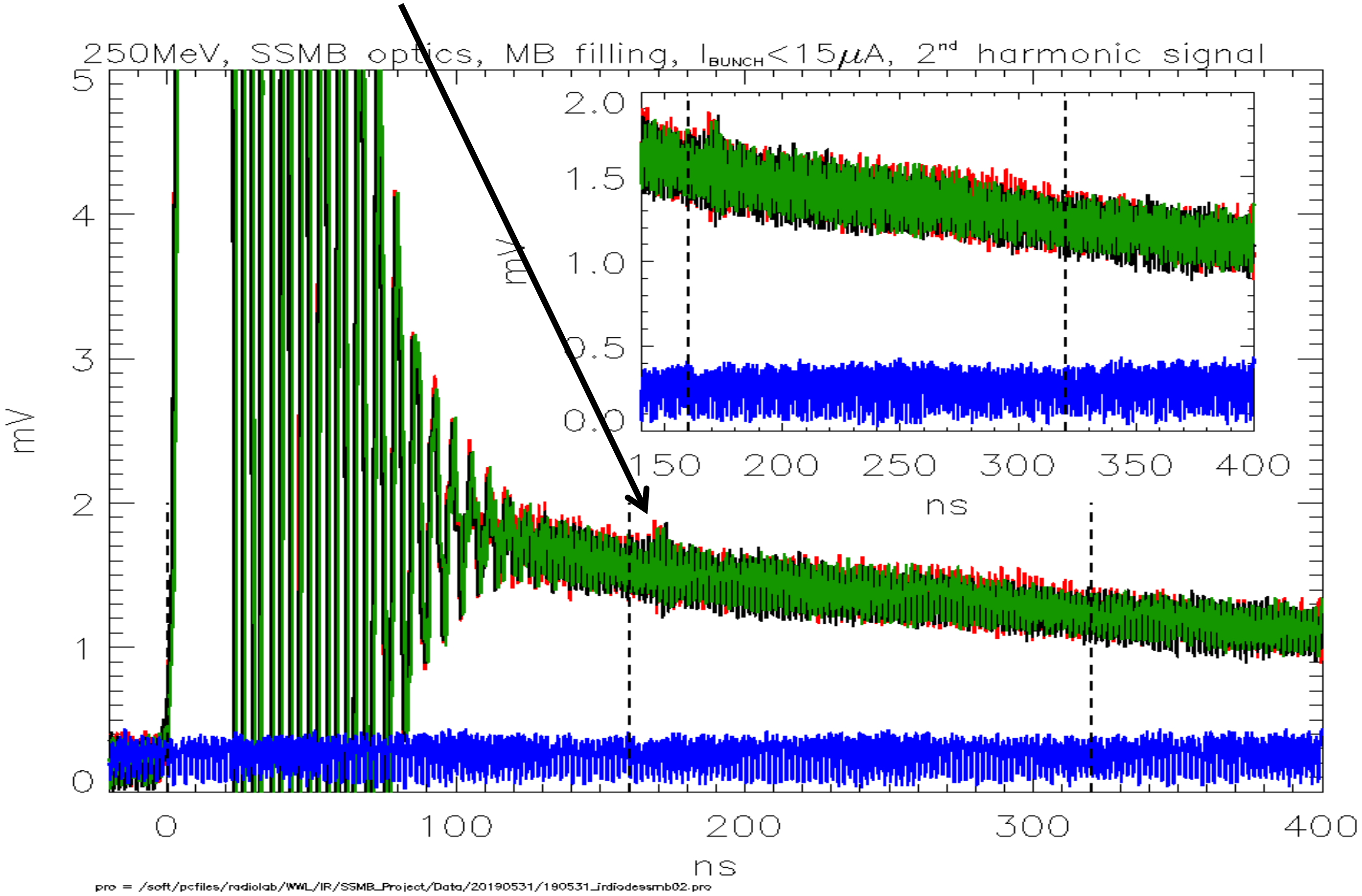
- Switch on Laser: during early comissiong at 10Hz rate during later runs at 1.25 Hz

- If matched to e-orbit Laser beam increases beam **energy width** which is seen as **horizontal beam widening** at dispersive imaging systems -> **maximize horizontal beam width** by steering laser system mirrors to achieve optimum beam laser overlap. This is only possible in **ramp optice** because only there **dispersion $\neq$ 0 at ID**.
  No further possibility to controll e-/laser overlap later in SSMB optic.

- Switching to **SSMB optic** and lowering alpha to very small values. Activate photo diodes for detection.

- Systematic simultaneous **scan of dispersion at ID** (to sub-mm accuracy) using prepared combinations of Quadrupoles, **horizontal orbit** and **alpha0** untill coherent signal appears **(time consuming !)**

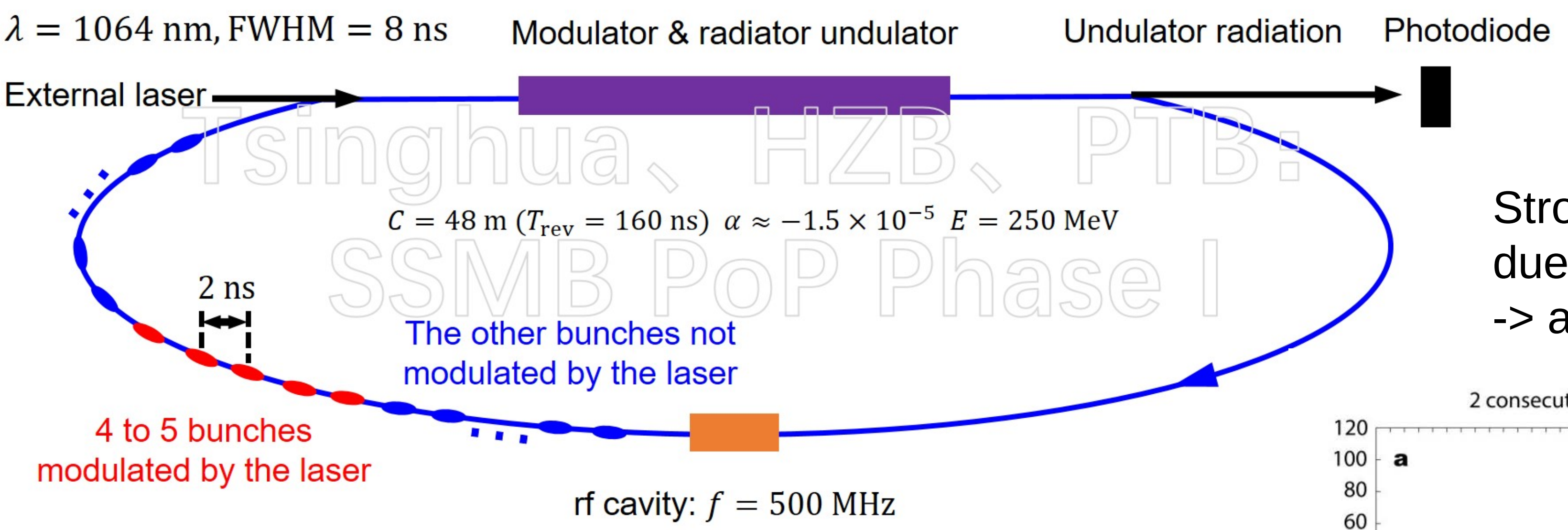
Friday, May, 31st. 2019, we saw **coherent signal for the first time !**



- homogenous filling,
  ~ 1 mA in 80 bunches
- $\alpha_0 = 2*10^{-5}$
- Dx<1mm at undulator
- signal detected at λ=532 nm

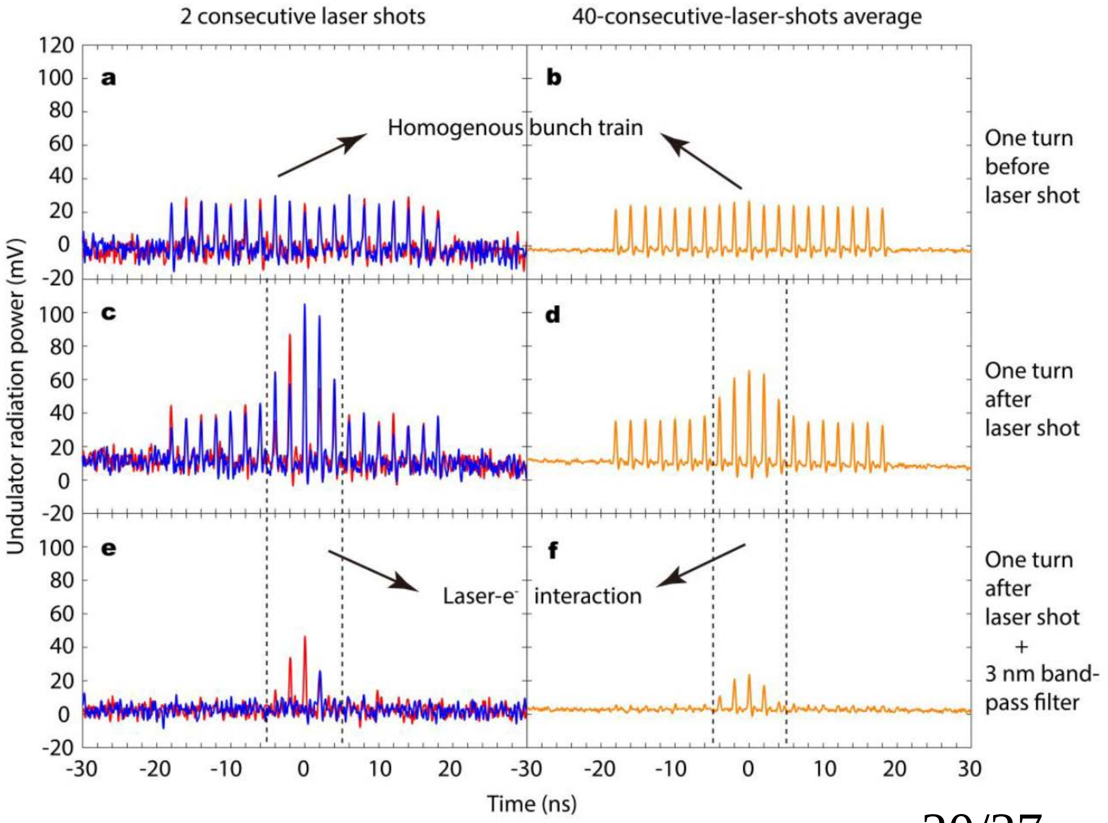
Alex, Xiujie,Ji, Jörg, Arne

Success only two years after first SSMB Meeting



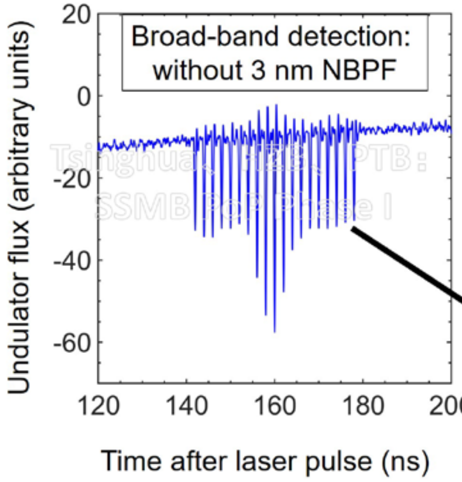
Tsinghua、HZB、PTB: SSMB PoP Phase I

Strongly fluctuating coherent signal due to unstable Laser emission -> averaging needed



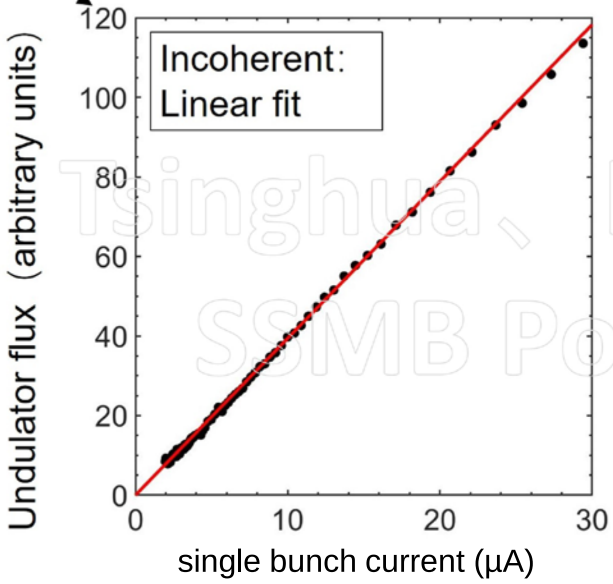
- The undulator radiation (2nd harmonic) intensity amplification of the **4 to 5 bunches in the middle of the bunch train** one turn after modulated by the laser indicates the formation of microbunches and generation of coherent radiation.
- One important feature of the coherent radiation: narrow-banded.

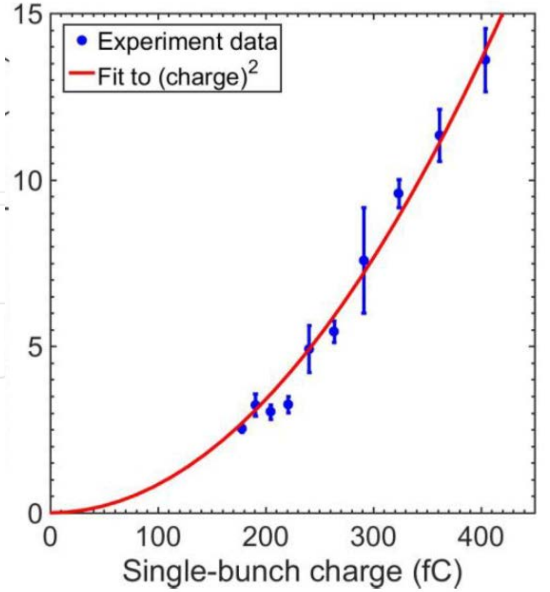
- The **quadratic beam current scaling** of the coherent radiation demonstrates unequivocally the formation of microbunching as well as its small band width
- The coherent signal comes from 2nd harmonic radiation. 1. harmonic radiation is blocked together with the Laser light. **Fundamental mode is expected to have a much higher radiation power**

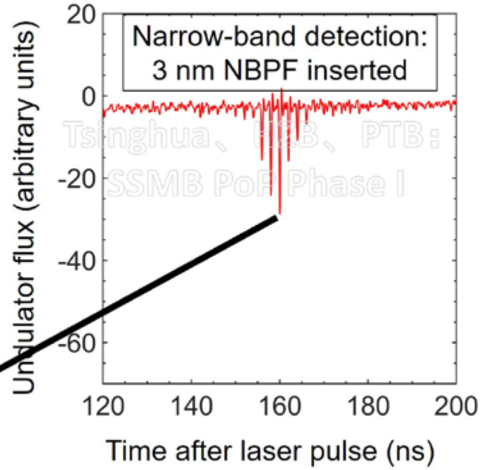


Broad-band incoherent radiation of usual bunch

Narrow-band coherent radiation of microbunches



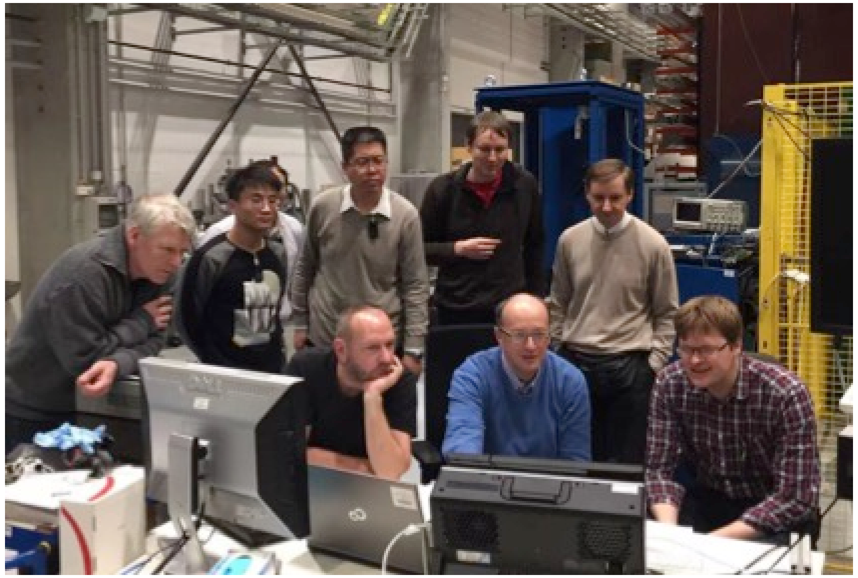


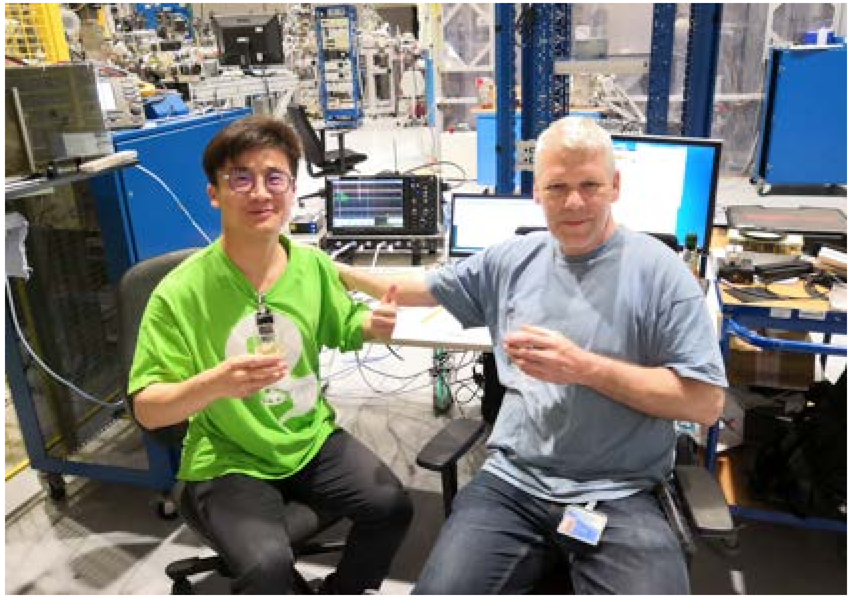


Significance of SSMB PoP Phase I (A. Chao)

- Our PoP test is essentially different from the other single-pass microbunching experiments. The key point here is to demonstrate that in a touchy isochronous storage ring, a microbunched electron beam can stay microbunched with definitive microbunching phase.
- Once the one-turn microbunching phase is established with the electron beam stored stably in the required storage ring lattice, a multi-shot laser is expected to provide the microbunching bucket for 1000 turns in Phase-II using the same ring configuration but replace the single-shot laser by a 1000-shot laser.
- The Phase-I experiment demonstrates phase stabilization in the optical wavelength range, validating the scaling from RF buckets to optical microbuckets and microbunches.

Very exciting working atmosphere – great team !

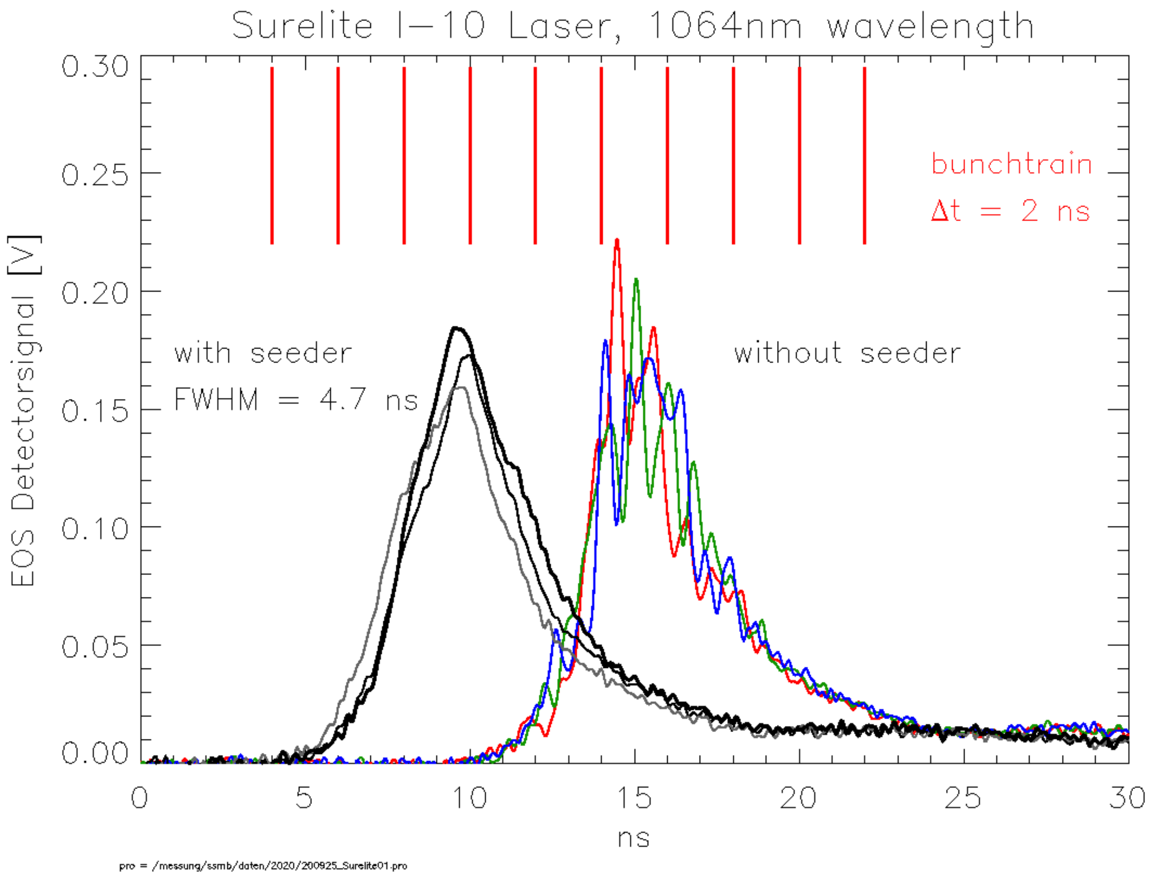




First Indication on 31st May, 2019
Definite Proof on 18th Aug, 2019

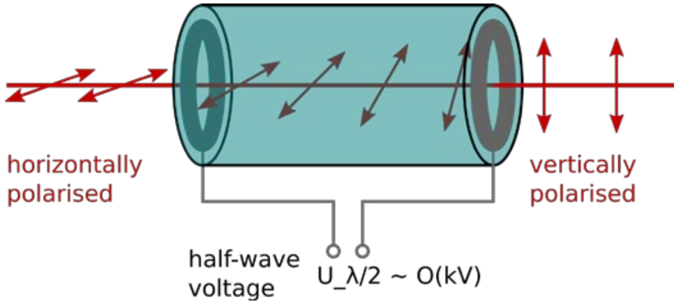
Recent developments

- DAWA Laser removed and sent back to Tsinghua university. An new seeded and more stable Laser aquired and prepared for installation in the MLS bunker (during first week **January 2021**)

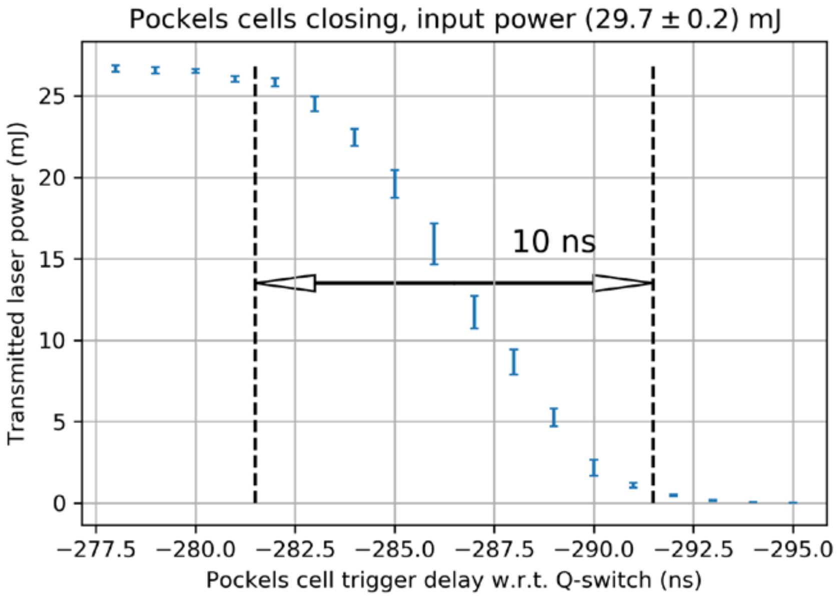


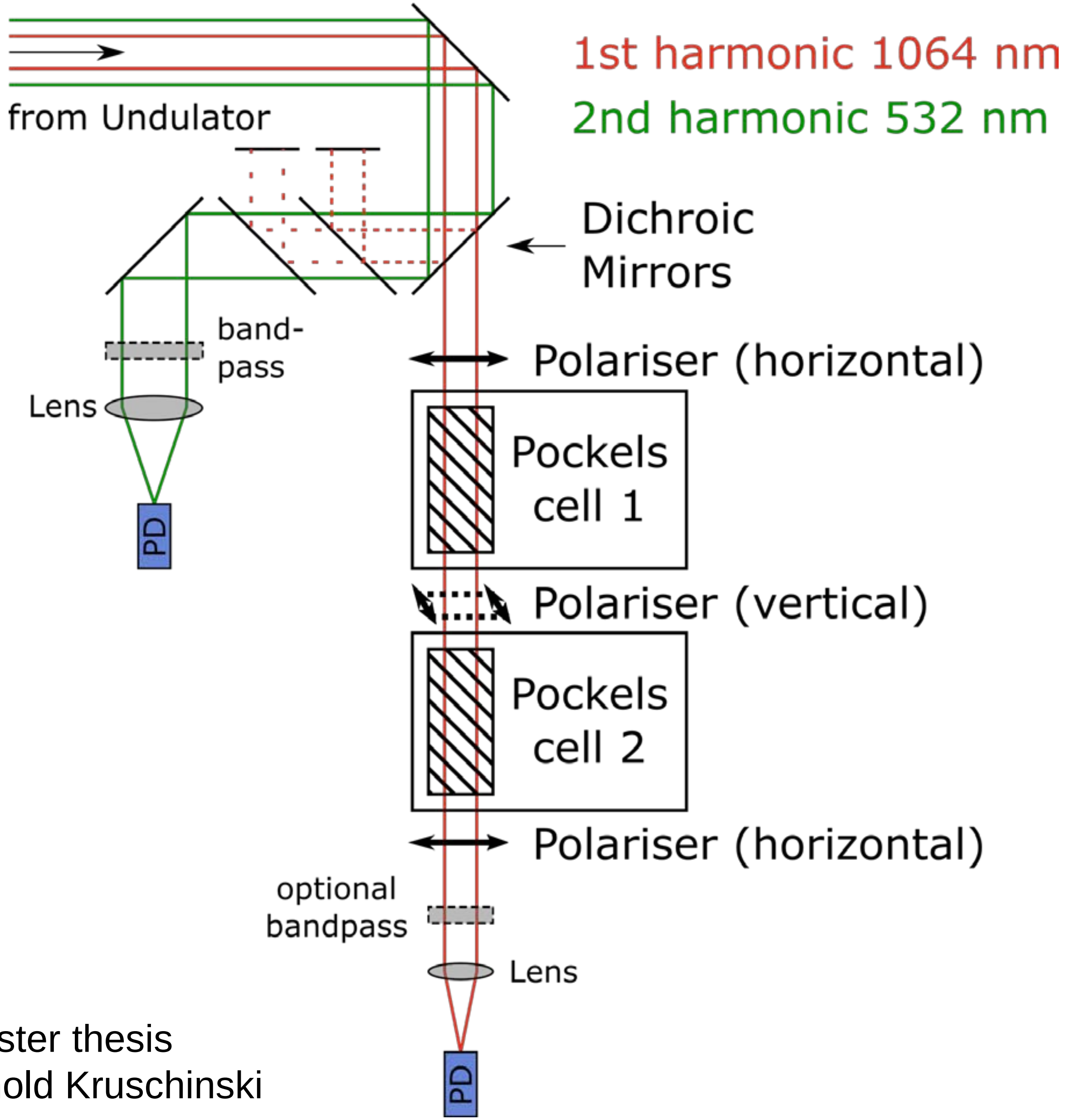
- ✓ General specification approved
- ✓ Confirmed puls length <5ns
- ✓ Pulsform improved to true Gaussian

New detection setup using **fast optical switches** developed to **block out laser pulse** thus allowing
first order detection of coherent signal at 1064nm



Mounted between crossed polarisers: Fast optical switch O(ns)





Master thesis
Arnold Kruschinski

Phase-II (planned)

- Replace the single-shot laser by a 1000-shot laser, but use the same MLS ring lattice.
- Can test only a quasi-SSMB. Microbunch lifetime ~ 1000 turns. Full SSMB requires a dedicated ring and a CW laser.
- The SSMB Collaboration plans to launch Phase-II. Very unfortunately delayed by COVID19.

Summary

- The Steady-State Microbunching in storage rings has the potential of starting a new era of accelerator photon science from THz, IR, to EUV.
- The mechanism of SSMB has been demonstrated experimentally in electron storage ring MLS. It is the first key advance of developing an SSMB high-power coherent radiation source.
- PoP Phase I capabilities will be strongly improved by using seeded laser and a first harmonic detection scheme (Installation January 2021)
- SSMB PoP Phase II is under preparation and will be conducted in the near future.