Development of Photo Injectors for FLASH and European XFEL

Frank Stephan for the PITZ collaboration

Siegfried Schreiber (Siggi) → † 23.4.2024

2019

Accelerator R&D is a **team effort**:
Sincere thanks to all **cooperation partners** participating in photo injector research !

Outline of the talk

high brightness electrons sources for FLASH and European XFEL

- Why the photo injector R&D was started at DESY ?
- How it was done ?
- Progress on emittance reduction
- Summary of gun developments
- Photo cathode laser developments
- Photo cathode developments
- One example: application of high brightness electron sources beyond FELs

Why photo injector R&D was started at DESY?

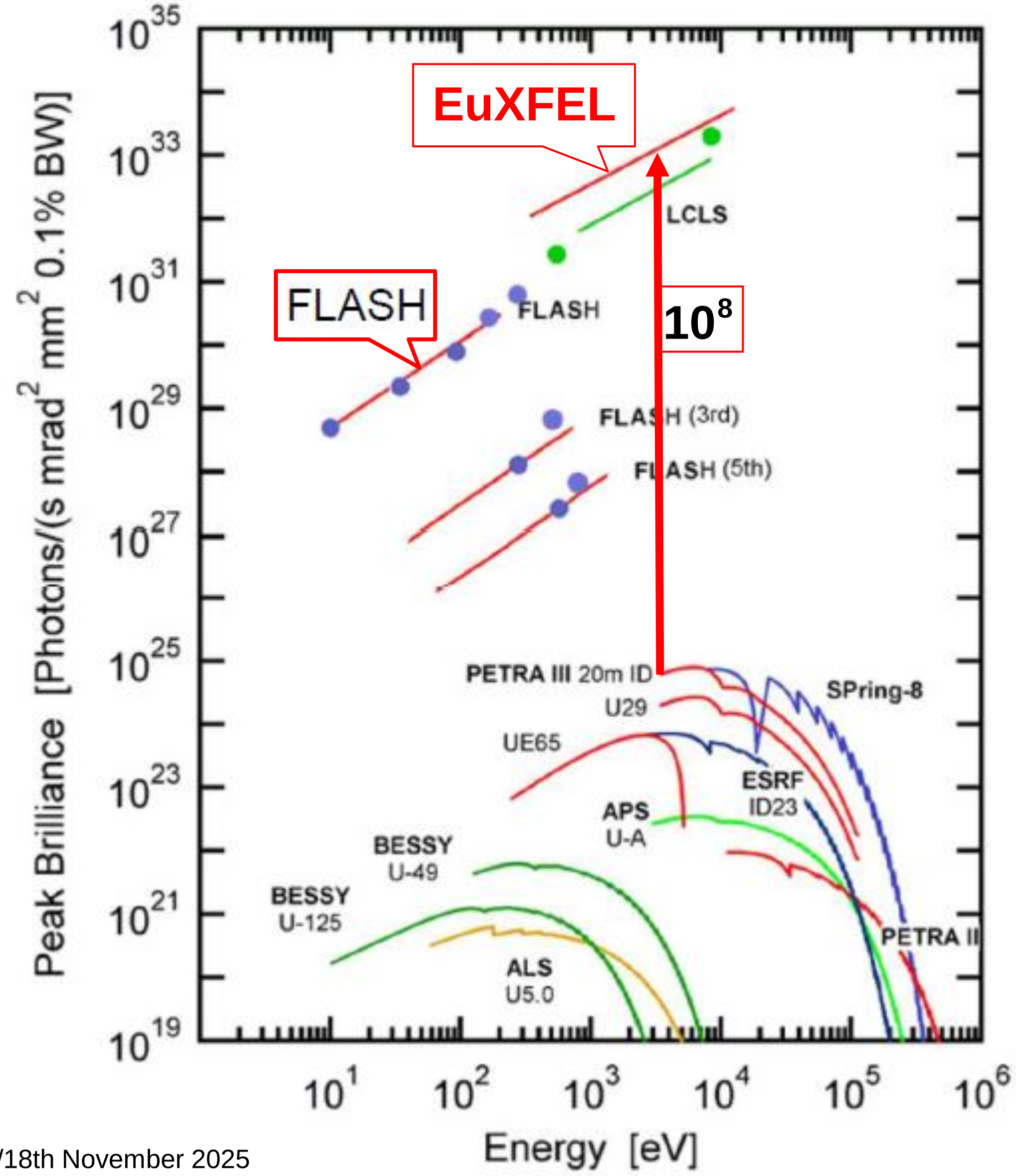
Motivation: Why the photo injector R&D was started at DESY ?

European XFEL - a next generation light source with unique capabilities

Promises 25 years ago,
→ now being realized:

- wavelength down to 0.1 nm
  ➔ **atomic-scale resolution**
- ultra-short pulses (≤ 100 fs)
  ➔ **ultra-fast dynamics**,
  "molecular movies"
- ultra-high peak brilliance
  ➔ investigations of matter under
  extreme conditions (**Xe^{21+}**)
- transverse spatial coherence
  ➔ imaging of single nanoscale
  objects, possibly down to
  individual macromolecules
  (**no crystallisation needed !!**)

Why brilliance is ~10E+8 higher ?
Synchrotrons: $P \sim N \cdot e^2$
FELs (coherence):
$$P \sim (N \cdot e)^2 = N^2 \cdot e^2 ,$$
$$N \sim 10^8$$



SASE FEL: How does it work?

Coherence is all we need !!

Courtesy: Jörg Rossbach

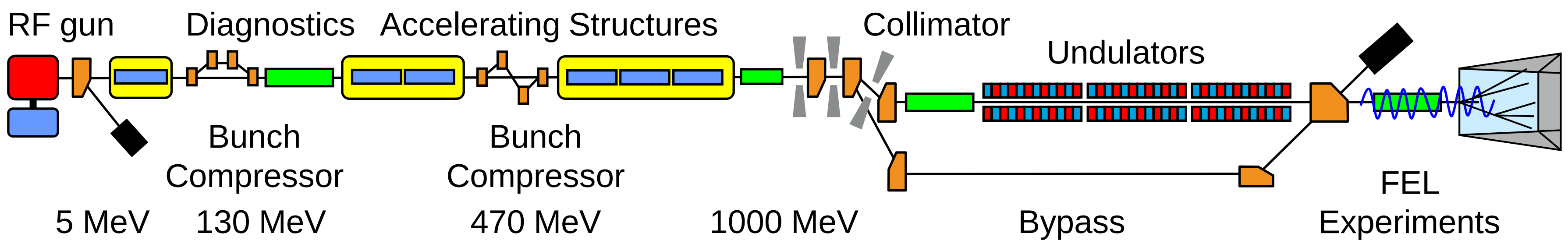
XFEL key component: → high brightness electron source

Why electron injector is so important …. ???

➔ property of linacs: beam quality will DEGRADE during acceleration in linac

➔ **electron source has to produce lowest possible emittance !!**

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



- **electron source**
- **accelerating sections** → **e.g. wakefields, coupler kicks**
  - in between: **bunch compressor(s)** → **e.g. coherent synchrotron radiation (CSR)**
- **undulator** to produce FEL radiation
- electron **beam dump**
- **photon beamline(s)** for the users

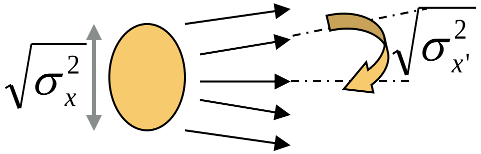
} **increase normalized transverse emittance**

Emittance – a measure of the beam quality

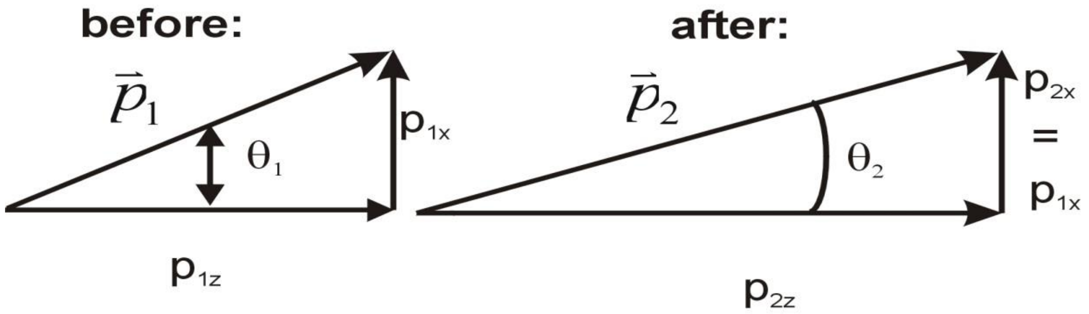
ε = 6 dimensional phase space volume occupied by given number of particles

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

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

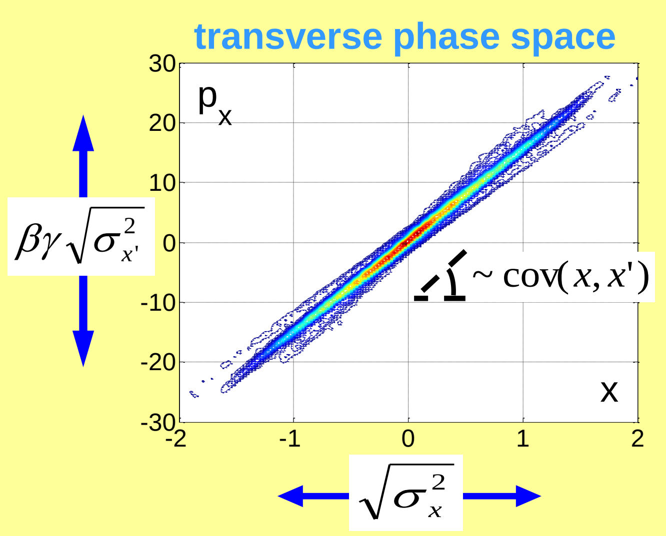


effect of <u>acceleration</u> on transverse emittance (adiabatic damping):



$\theta_2 < \theta_1$

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



$\Rightarrow$ normalized RMS transverse emittance:

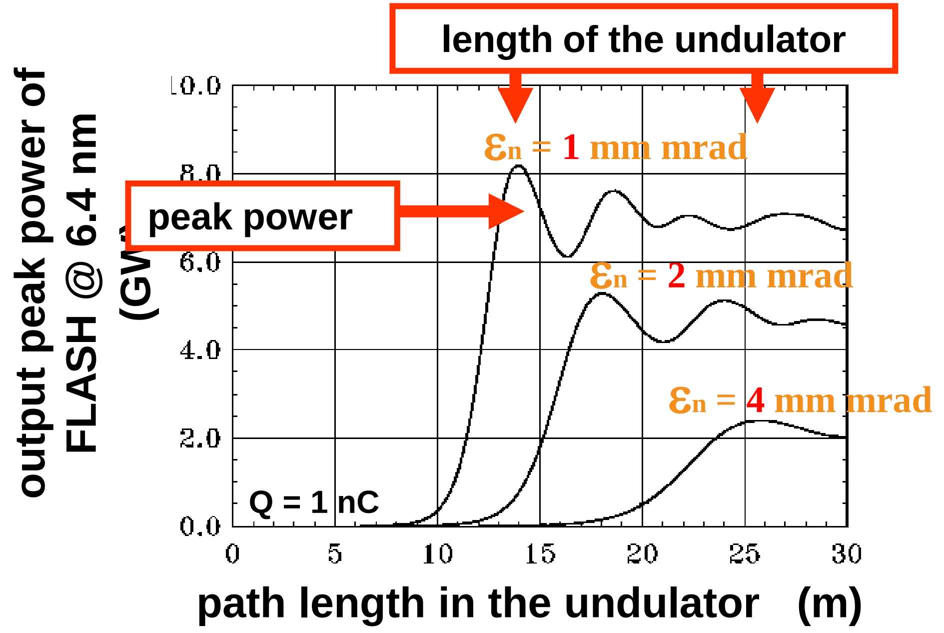
$$\varepsilon_x^n = ß \bullet \gamma \bullet \sqrt{\sigma_x^2 \bullet \sigma_{x'}^2 - \mathrm{cov}^2(x, x')}\ ; \quad ß = \frac{v}{c}, \quad \gamma = \frac{1}{\sqrt{1-ß^2}}, \quad x' = \frac{dx}{ds}$$

(ε^n is conserved in general)

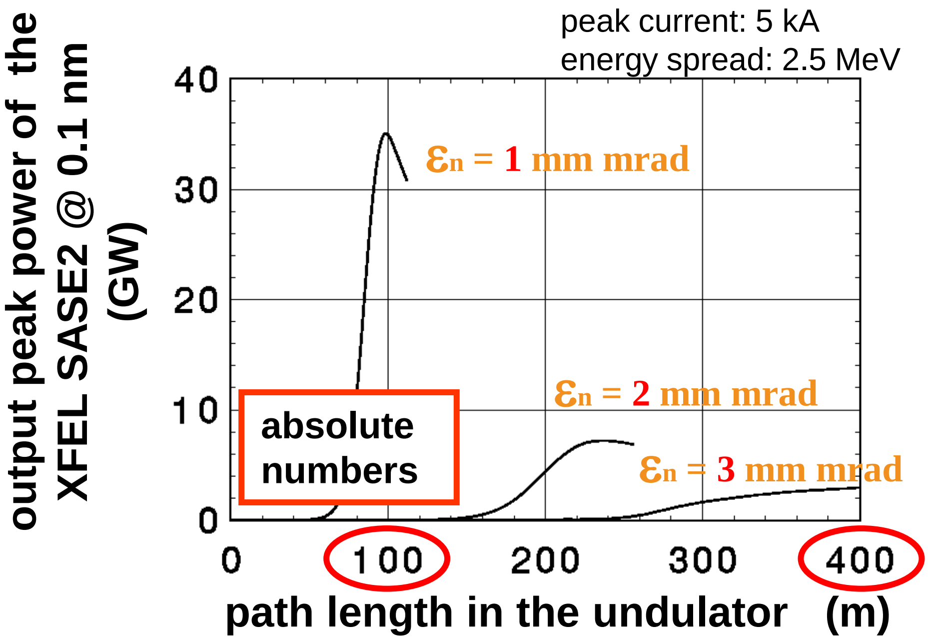
Why emittance must be small …

smaller transverse emittance ➔ higher X-ray power, shorter undulator needed, shorter wavelength possible

FLASH



EuXFEL

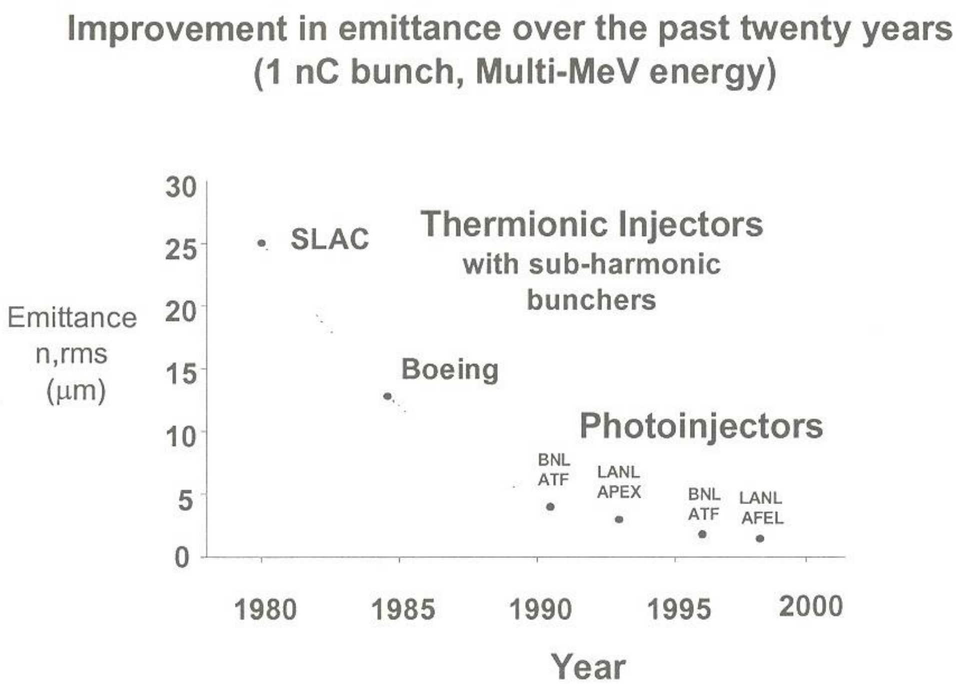


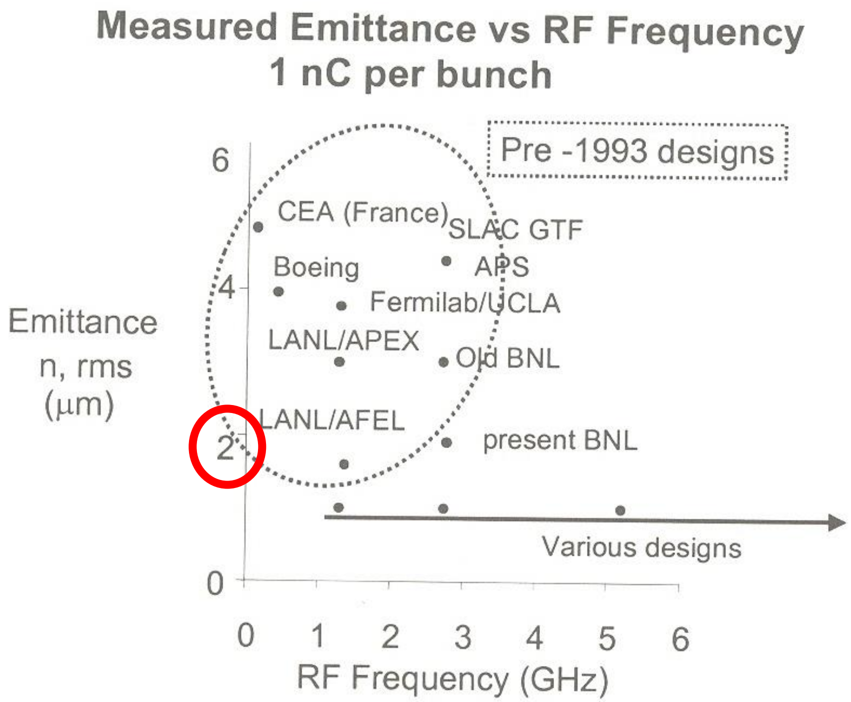
- **original EuXFEL goal:** **0.9 mm mrad@injector ➔ 1.4 mm mrad@undulator**
- **if even smaller emittance ⇒ shorter wavelength, higher repetition rate**

Situation on emittance in 1999

From ICFA workshop on high brightness beams at UCLA in autumn 1999

Summary talk of P. O'Shea (U Maryland, USA) on electron source developments:





"Goal for community in next years:

Get transverse normalized emittance of 1 mm mrad @ bunch charge of 1 nC !!!"

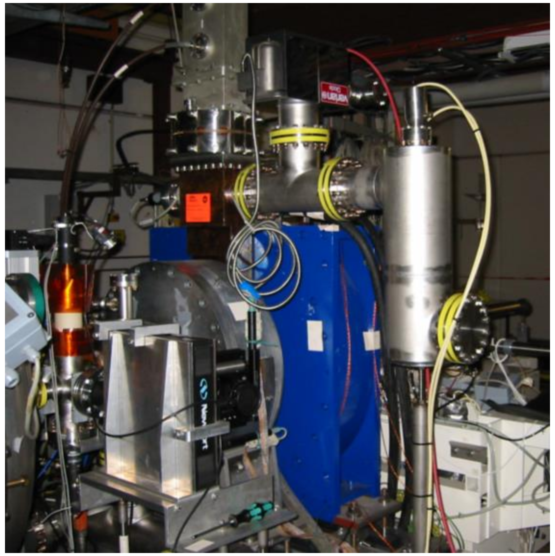
How photo injector R&D was done at DESY?

Electron sources for TTF/FLASH at the end of last century

Thermionic source was driving TTF, FNAL developed first PI in use at TTF, DESY development in parallel

- The TESLA Test Facility (TTF) was driven by a thermionic source (250keV + SHB + scCC) from Orsay (Terry Garvey et al.):
  - Goal: demonstrate **high current** transport through the super-conducting (SC) cavities which were under development
  - Parameters: 217MHz, **8mA**, 800µs

- In 1998: first Photo Injector (PI), developed by FNAL (Helen Edwards et al.), was installed at TTF:
  - Goals: * test transport of **high bunch charges** through SC cavities (wake fields),
    * get first experience with PI technology: 50MV/m, **≤8nC**/1MHz, 1nC/9MHz, 800µs
  - Cooperation with the Max-Born Institute (MBI) started: → photo injector laser system

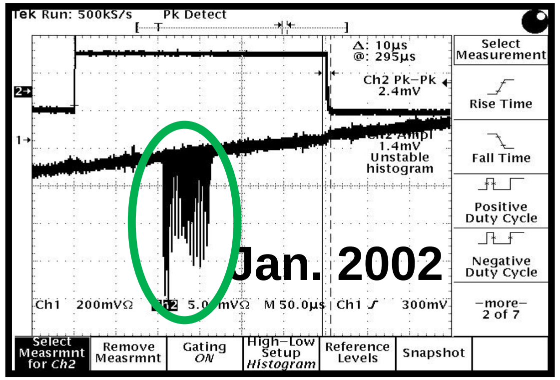


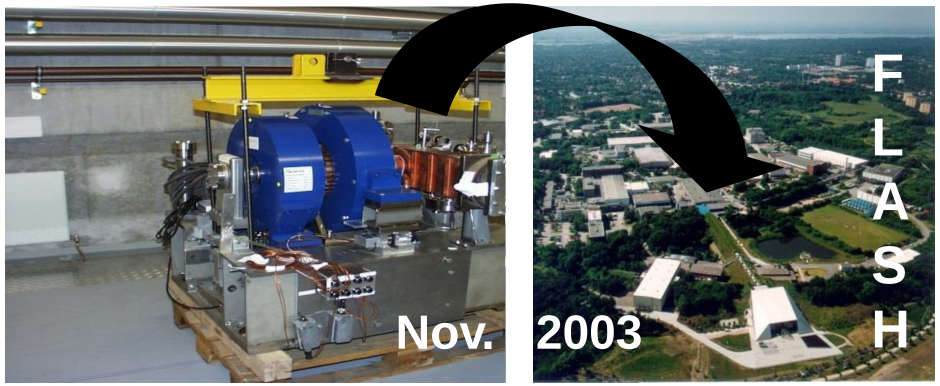
- In parallel, Klaus Flöttmann et al. @DESY developed PI with maximized symmetry (coaxial RF input coupler, no pick-up):
  - Goal: **minimize beam emittance**
  - Parameters: **60MV/m**, 1nC, 9MHz, 800µs

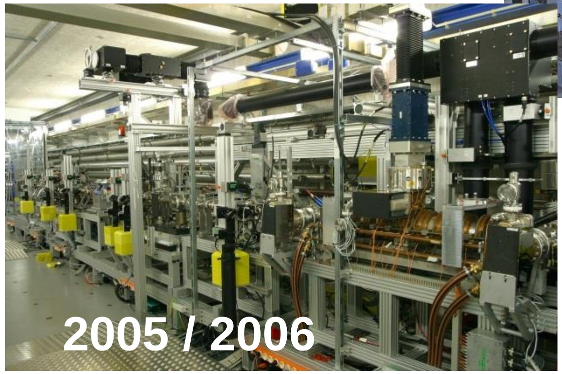
The early history of PITZ (Photo Injector Test facility at DESY in Zeuthen)

Photo Injector Development at DESY was concentrated in Zeuthen

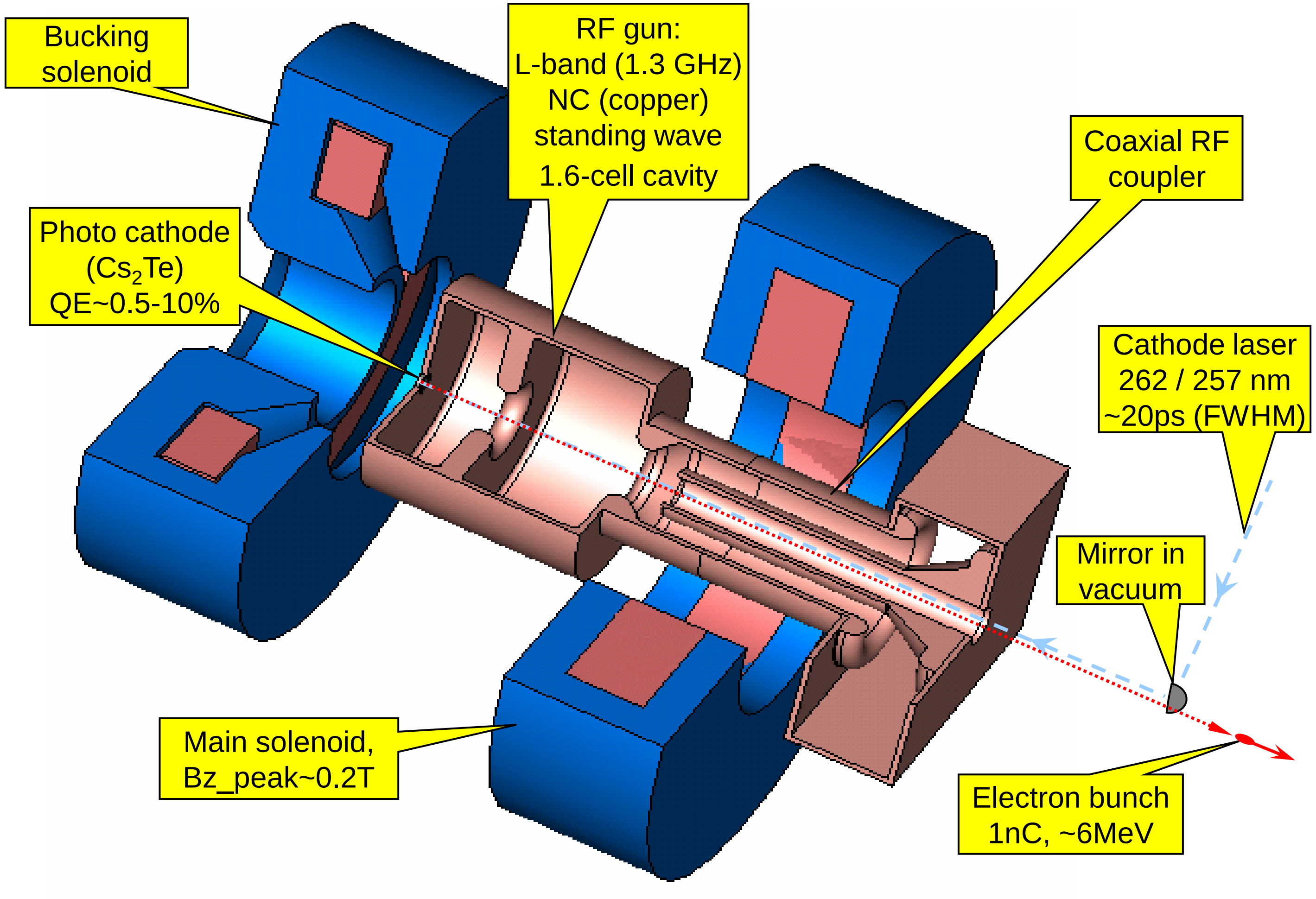
- Q1/1999: request to BMBF to build gun test facility independent from TTF
- September 1999: DESY directorate decision to build PITZ
- 2000: civil construction
- 2001: installation of infrastructure and first setup
- **13.1.2002: first photo electrons at PITZ**
- November 2003: first characterized RF gun is sent to TTF2-FEL (FLASH)
- 2005: first operation with booster cavity (~13 MeV) at PITZ
- 2006: provide spare RF gun for FLASH







Schematic setup of RF gun at PITZ



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, RF pulse length > 650µs)**
- **Very low normalized transverse emittance**

PITZ Collaboration Partners

Photo Injector R&D is a team effort !

- **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

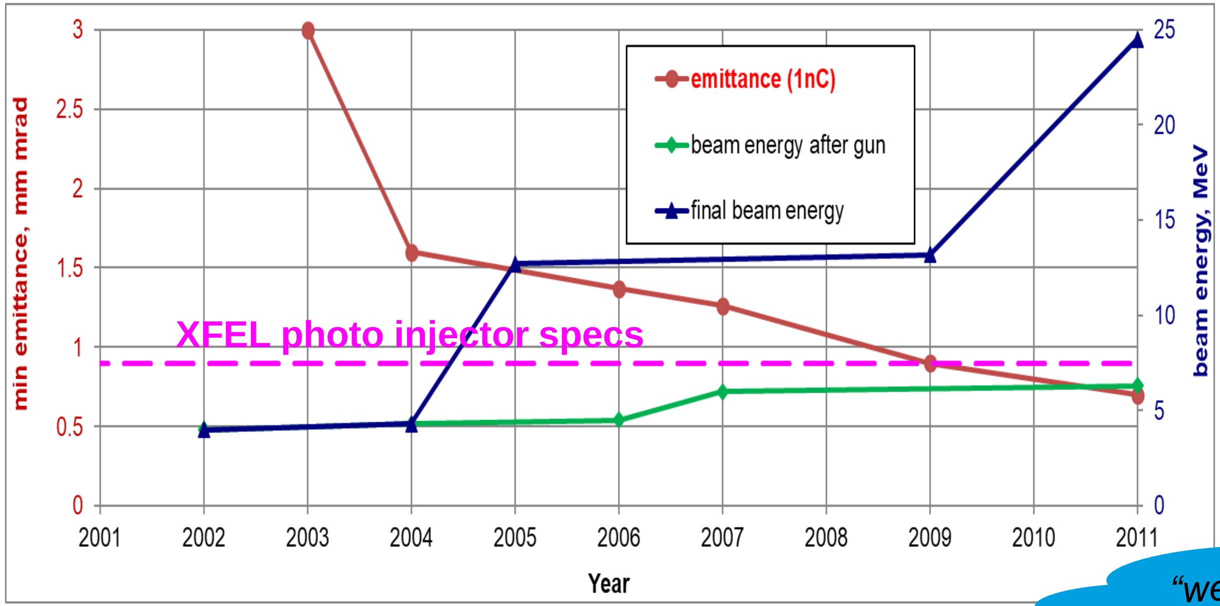
+ many new partners in FLASH RT,
e.g. Uni Geneva, MDC, Charité,
Uni Potsdam, MHB, DKFZ, …

- **International partners:**
  - **European XFEL GmbH** (Th. Feurer, Th. Tschentscher): THz@PITZ
  - **IAP Nizhny Novgorod + JINR Dubna**: 3D elliptical laser pulses, THz radiation (Currently suspended)
  - **INFN Frascati + Uni Roma II** (M. Ferrario, L. Palumbo): E-meter / TDS pre-studies
  - **INFN Milano** (C. Pagani, D.Sertore): 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, S. Rimjaem): personnel
  - **AANL (YERPHI)** (G. Karyan) **+ CANDLE** (B. Grigoryan), **Yerevan**: personnel
  - **LBNL Berkeley** (F. Sannibale): PWFA, NC CW Gun
  - **SLAC** (N. Holtkamp): LCLS-I undulators

Progress on emittance reduction

PITZ evolution 2002 – 2025, 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	2023	2024	2025	2026
gun	cavity		Gun2	FLASH	Gun1		Gun3.1	FLASH G3.2	Gun4.2	FLASH	Gun4.1	FLASH G3.1	FLASH G4.3 EuXFEL	G4.4 EuXFEL	Gun4.2	Gun4.6 EuXFEL	Gun4.5		Gun4.2			Gun5.1		Gun5.2	EuXFEL	Gun5.3
	Ez,MV/m		35	37	42-->60		43									60										
	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											
	Ebeam					~13MeV					~25MeV			22MeV*												
laser	temp ps		10	6/24\6	→			6/24\6	2/22\2	→					2/22\2	11*			~							
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 perforn			+emittance (EXFEL startup)					emittance (EXFEL working point)						
													+THz idea		+plasma				+THz project		+Rad.Biology						



Highlights:

- Increasing the brightness (decreasing the emittance)
- Improving gun stability and reliability
- Extending beam diagnostics
- Application of high brightness beams:
  e.g. PWFA, THz, radiation biology

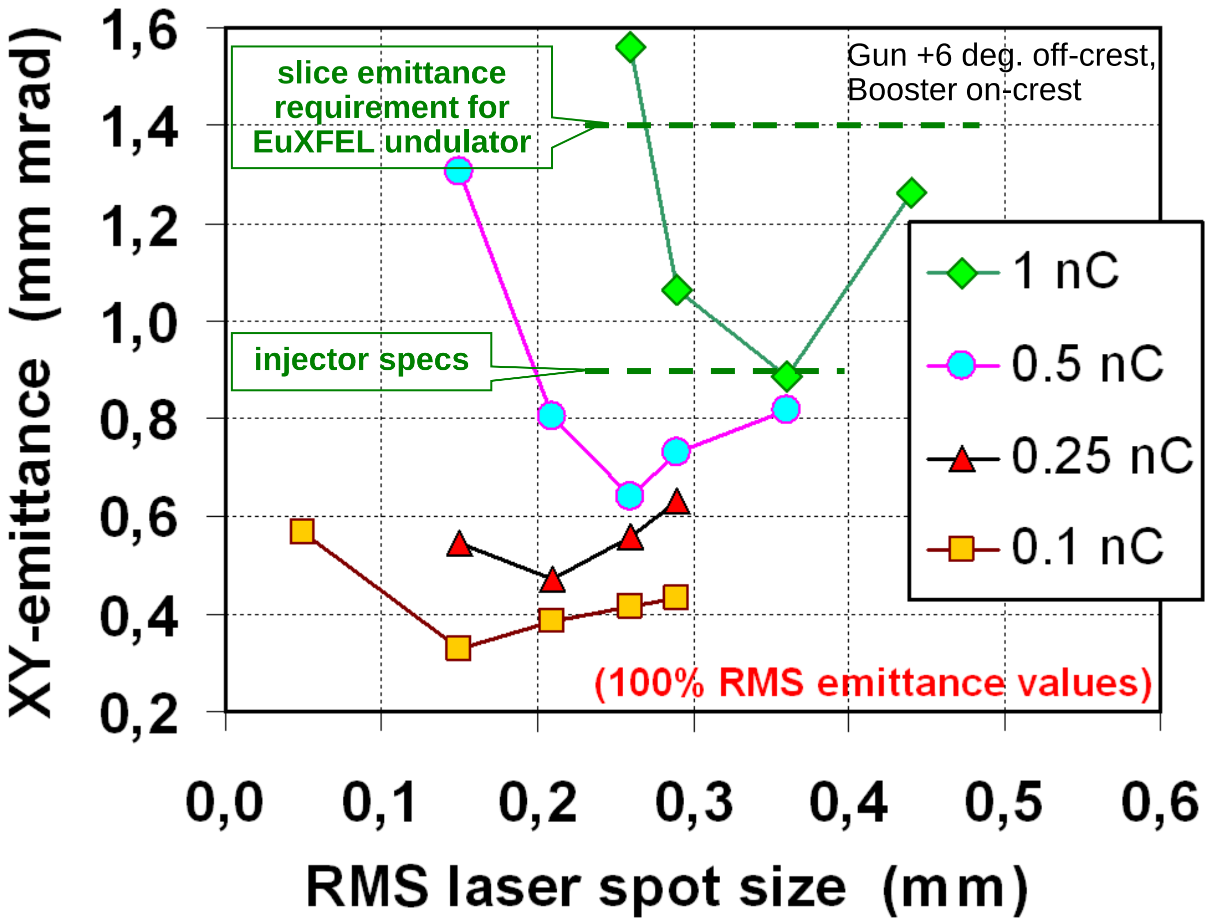
"we measure more and more of less and less…"

Courtesy: M. Krasilnikov

Emittance results from 2009

see e.g. S. Rimjaem et al., NIM A 671 (2012) 62-75

Normalized projected emittance vs. laser spot size@cathode for different bunch charges



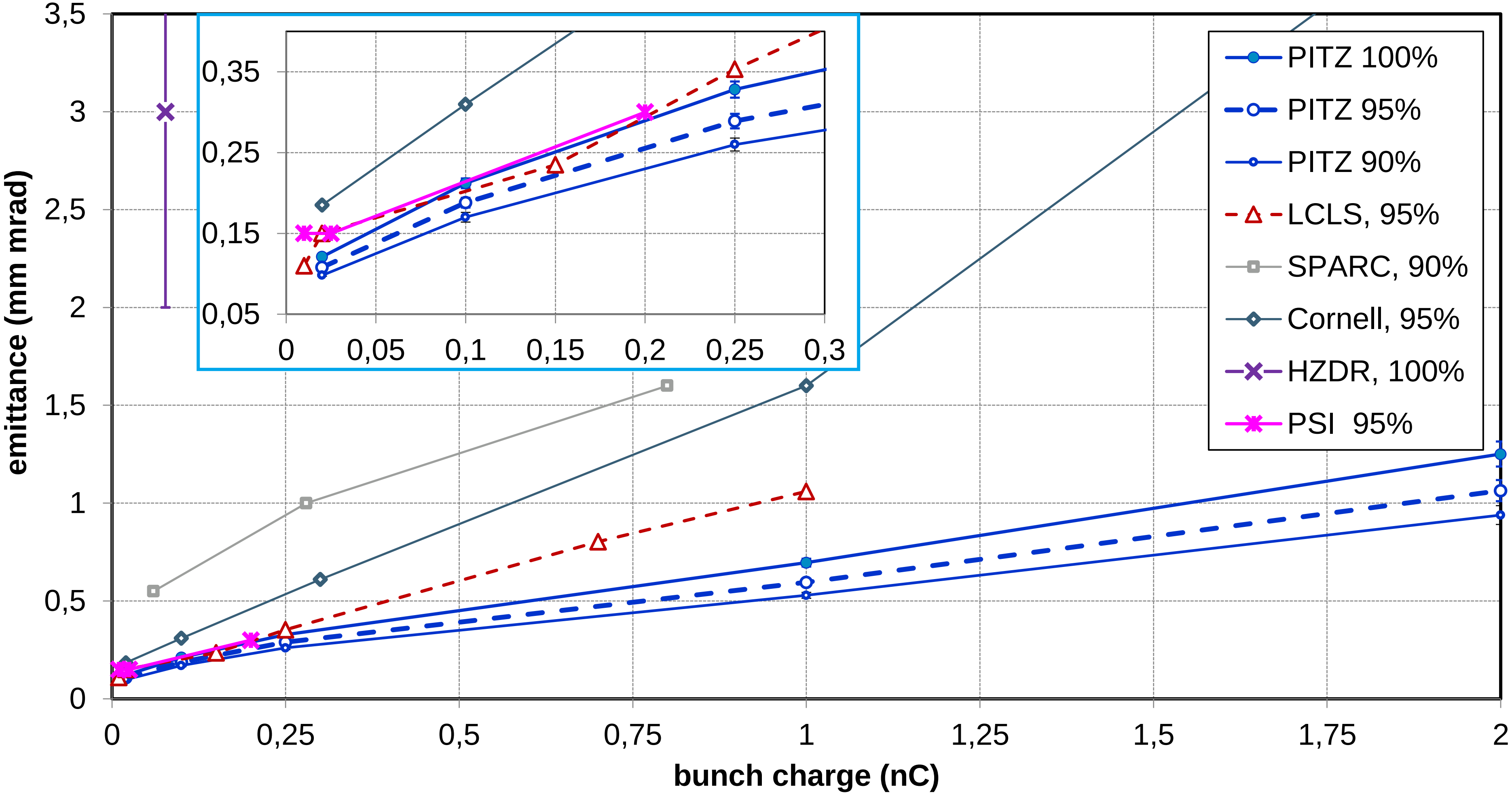
these results +
experience from LCLS
(only small degradation of slice emitt. from gun to undulator)

➔EuXFEL could be operated with 14 GeV beam energy (possibility to save ~33M€)

My point of view: it was a wise decision to still build EuXFEL with 17.5 GeV to use the energy headspace for future upgrades →CW

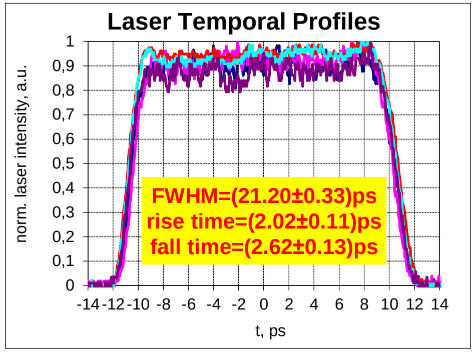
Measured RMS normalized emittance values

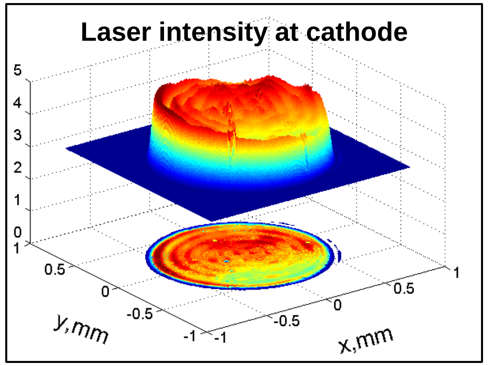
➔ PITZ world record on projected emittance from 2011 still valid



see M. Krasilnikov et al., PRST-AB 15, 100701 (2012)

Photocathode laser



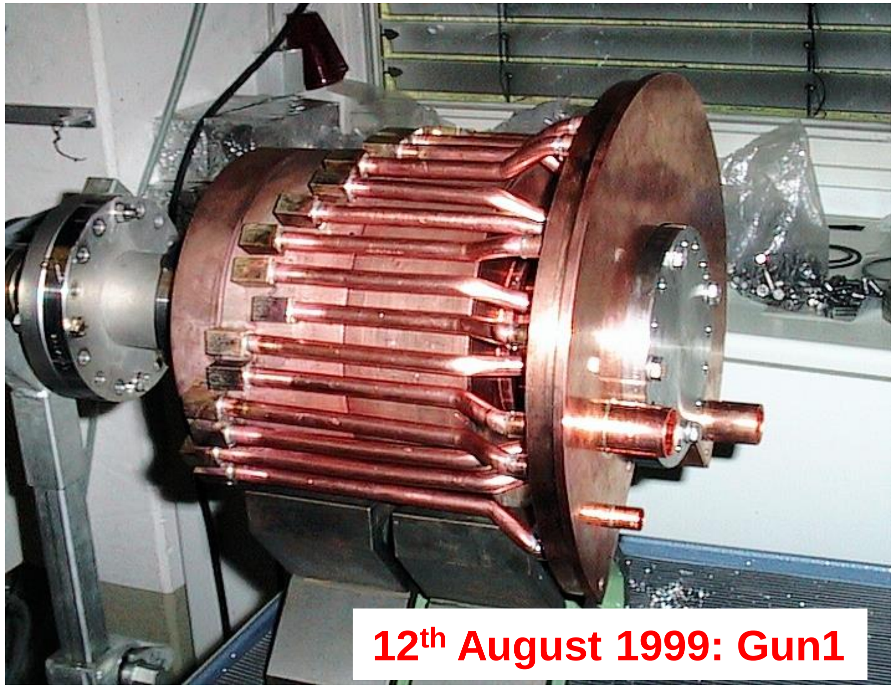


Minimum emittance measured at PITZ ($\sqrt{\varepsilon_{n,x}\varepsilon_{n,y}}$, 100%)

Charge (nC)	Emittance (mm mrad) with stat. error
2	1.25±0.06
1	0.70±0.02
0.25	0.33±0.01
0.1	0.21±0.01
0.02	0.121±0.001

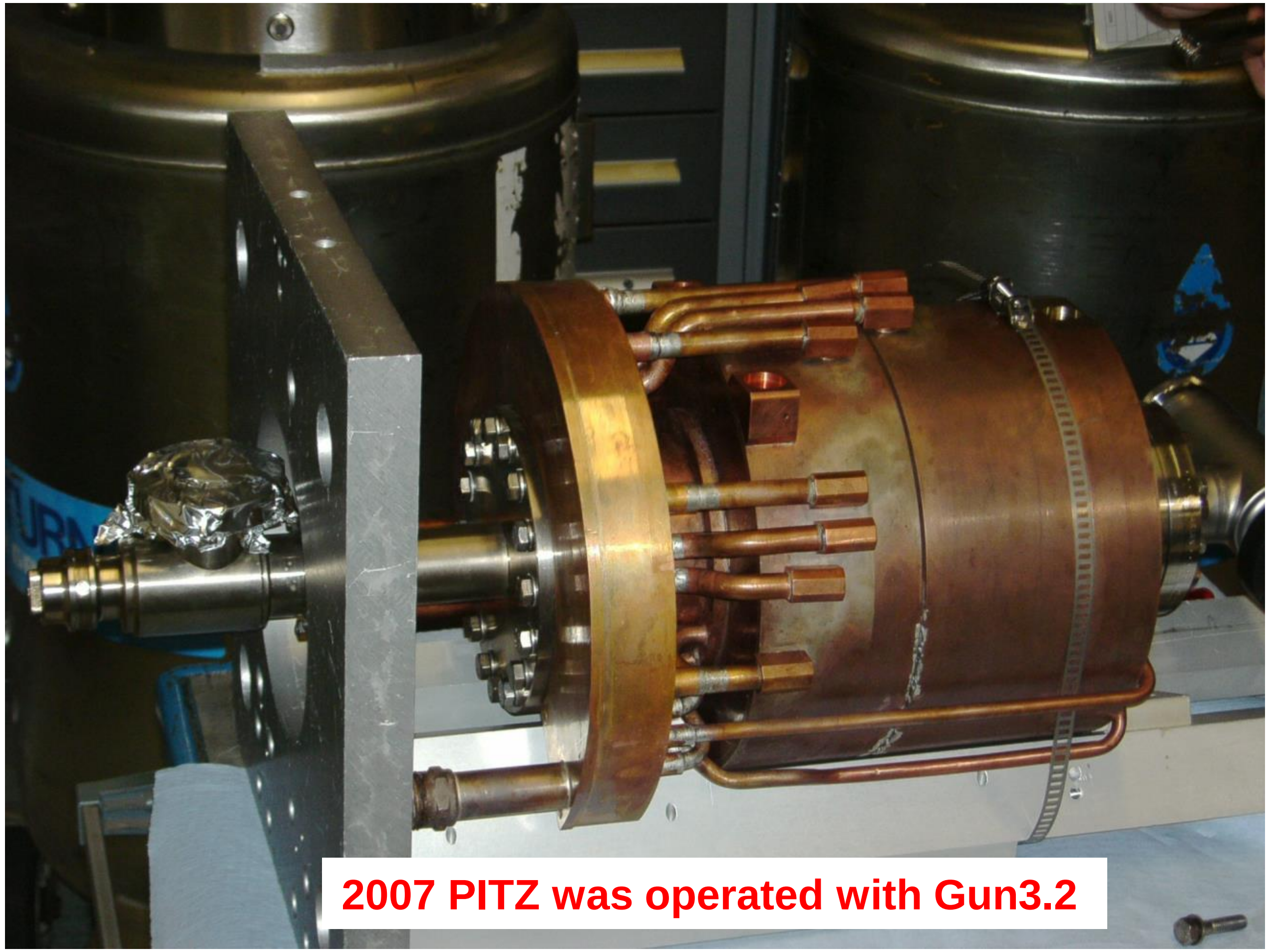
Summary of gun developments

RF gun cavity developments



Modifications:

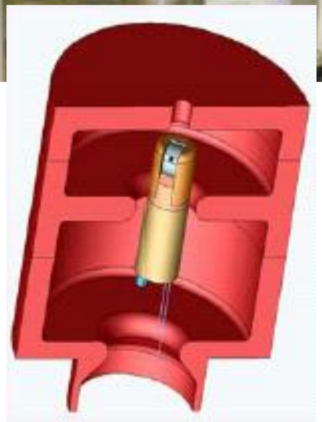
- Cooling water distribution
- Alignment capabilities
- Inner cell dimension "tuning"



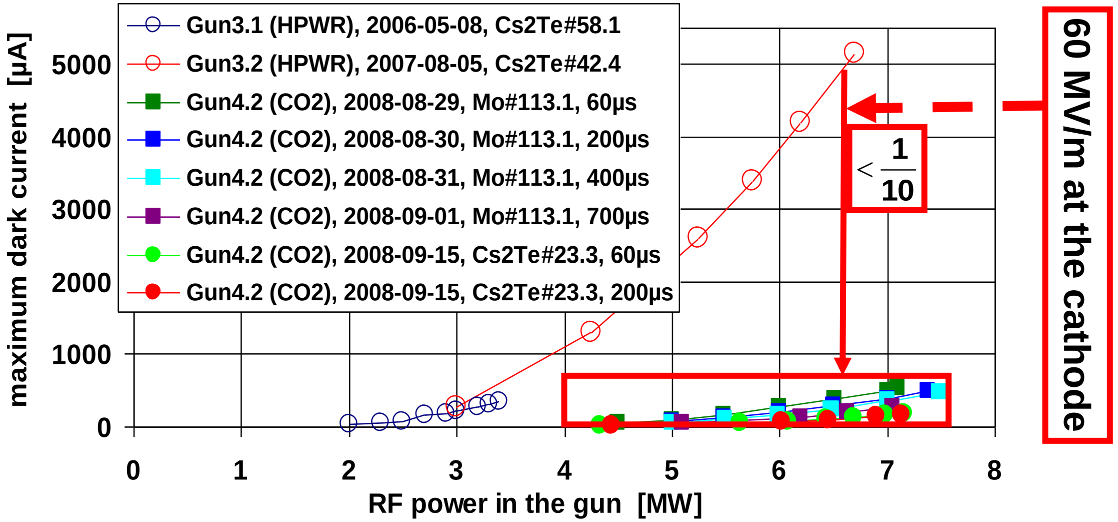
Reduction of dark current for high average power operation

2008: Dry-ice sublimation-impulse cleaning allows reduction of dark current by factor 10 (!)

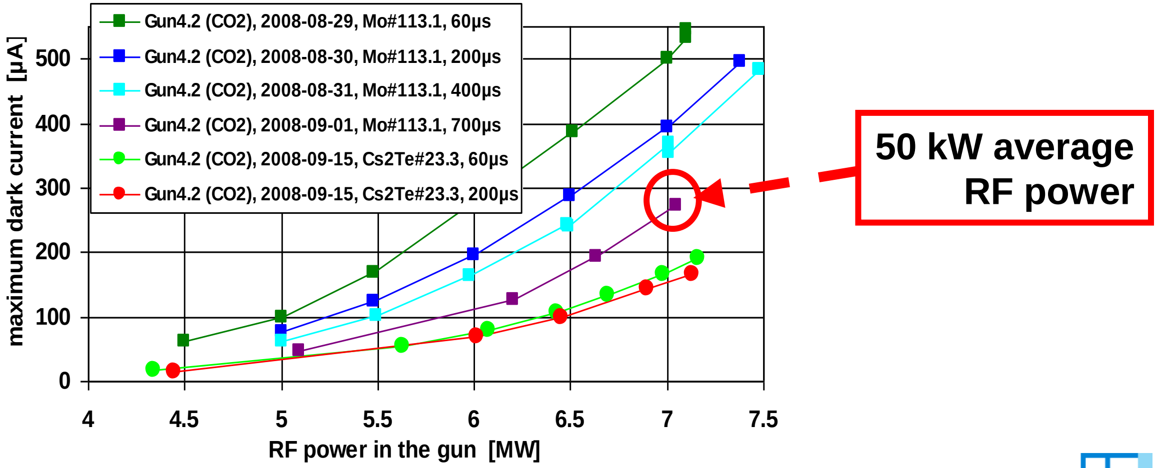
Vertical cleaning setup with 110º rotating nozzle.



Dark current measurements

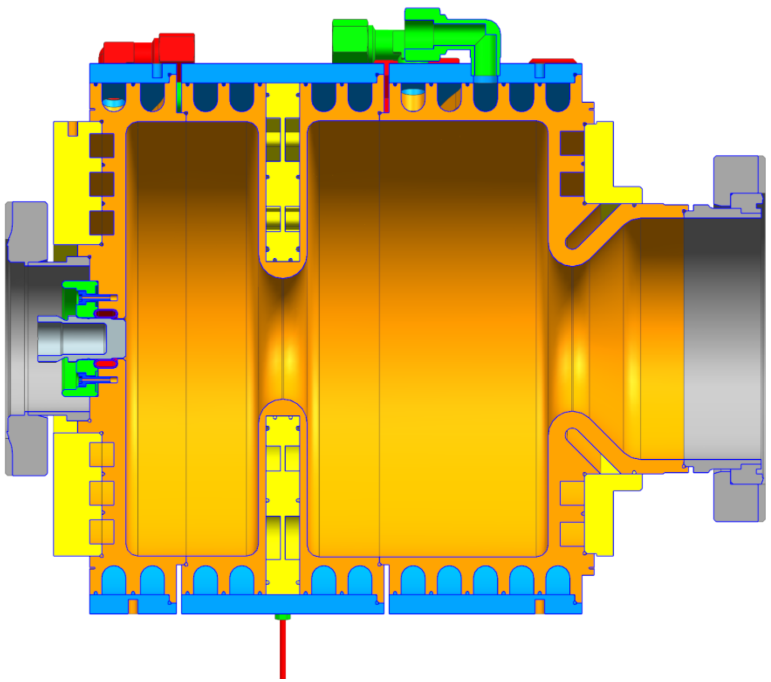


zoom:



Differences between Gun4 series and new Gun5 (= latest design)

Gun4



Gun5

Gun4

Gun5

min max

Electric field distribution for Gun4 and Gun5

- **Optimised cell shape:** higher RF **efficiency**,
  reduced peak **surface field** at same cathode gradient
- Direct field measurements inside the Gun: → **RF probe**
- Higher **cooling efficiency** (Gun 5: >60 kW average RF power, **1 ms @ 10 Hz**)
- **New cathode contact spring design**

[1] V. Paramonov, Yu. Kalinin, M. Krasilnikov, T. Scholz, F. Stephan, K. Floettmann. *RF Gun Development with Improved Parameters*. Linac 2008, p. 627, 2008

[2] V. Paramonov, N. Brusova, I. Rybakov, A. Skasyrskaya. *Physical specifications of the Gun 5 RF cavity for X-FEL requirements,* 2016

Courtesy:
Sebastian Philipp, Frieder Müller

Photo cathode laser developments

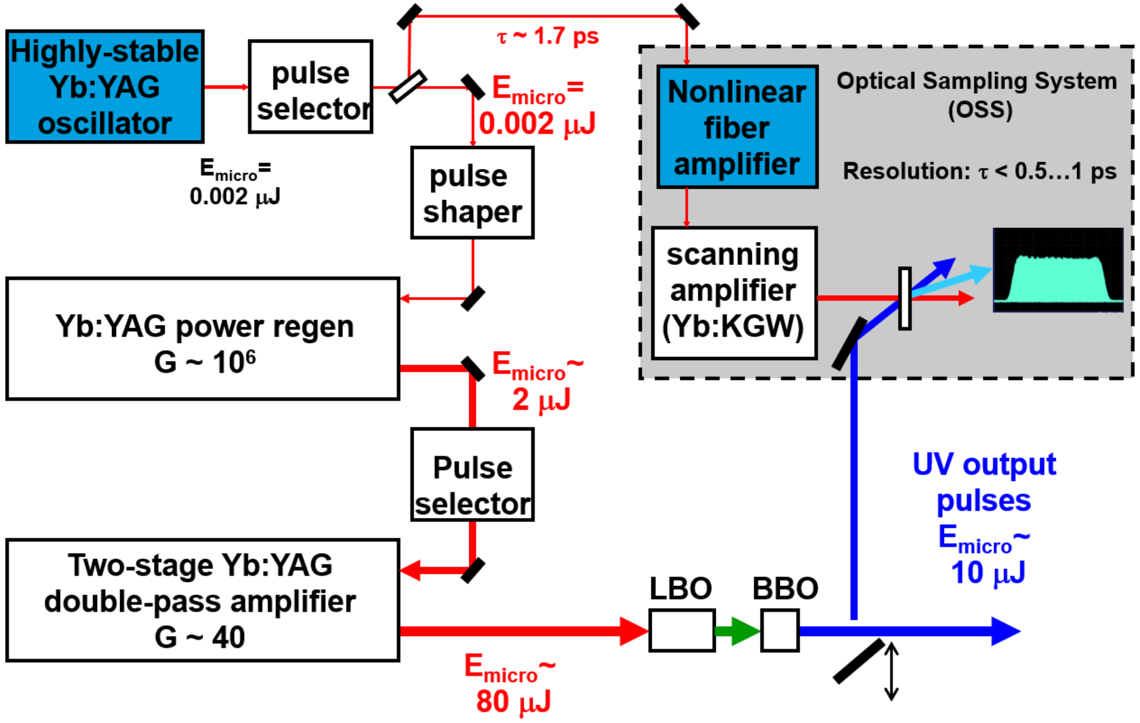
Photo cathode laser developments

A key component for the success of PITZ or any photo injector

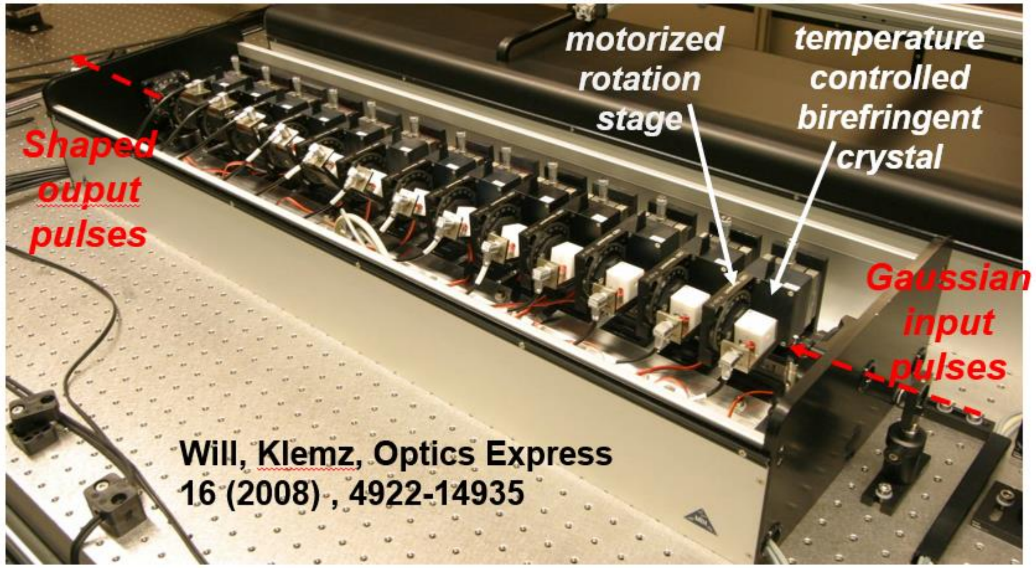
Max Born Institute, Berlin

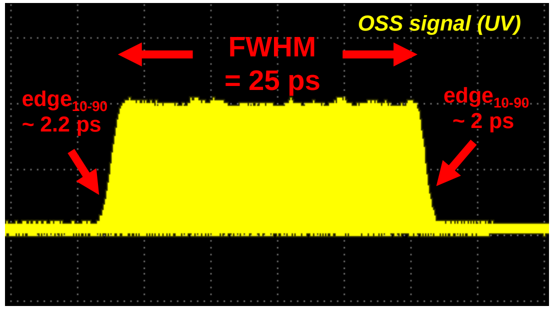
- development at MBI started 1998/99
- many intermediate steps realized + tested at PITZ
- MBI also provided other photo cathode laser systems for FLASH, EuXFEL, ELBE, HZB

@PITZ: Yb:YAG laser with integrated optical sampling system

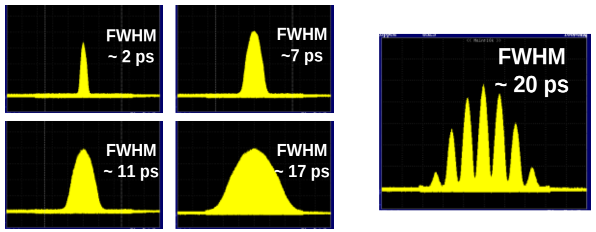


Multicrystal birefringent pulse shaper containing 13 crystals





Gaussian:

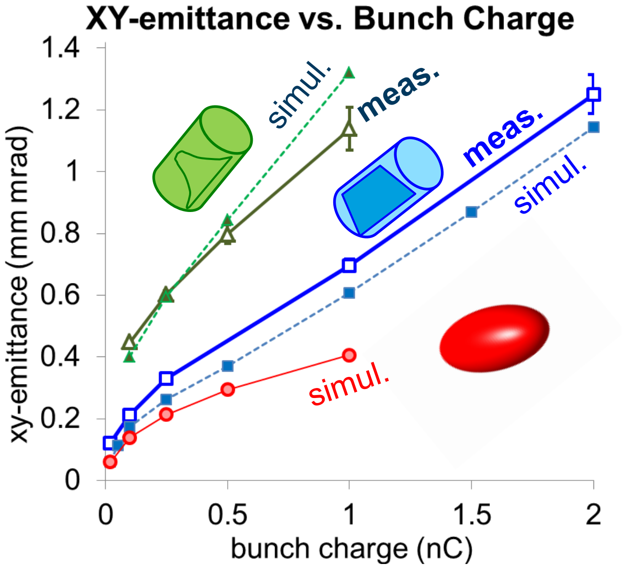


→ **very high flexibility**

Courtesy: Ingo Will

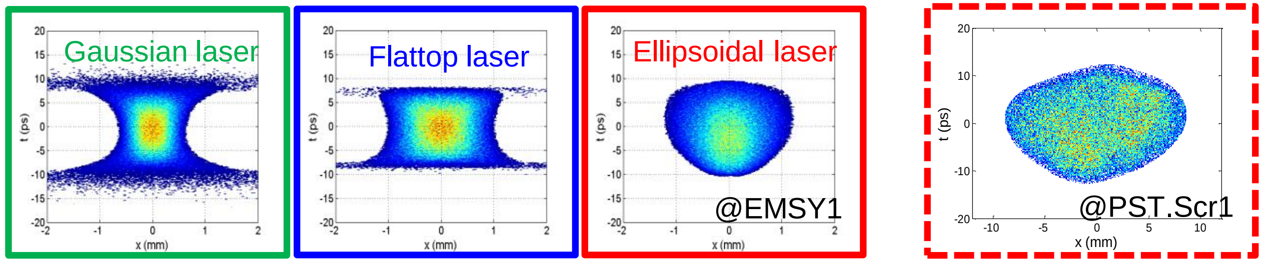
Towards 3D ellipsoidal electron bunches with IAP (Nizhny Novgorod)

Aiming for better transverse emittance, less halo, better LPS for bunch compresison



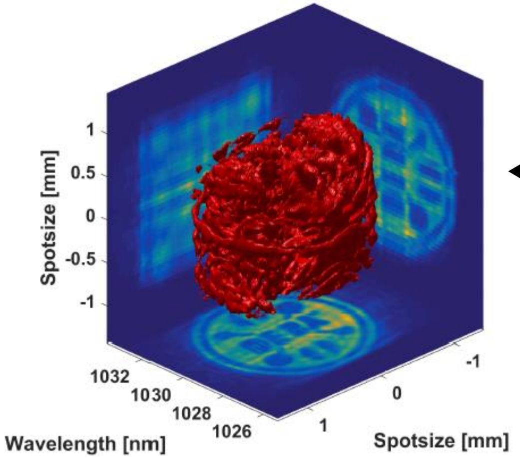
Proof of principle demonstrated with IAP system at PITZ in 2016 (single SLM → dual path)

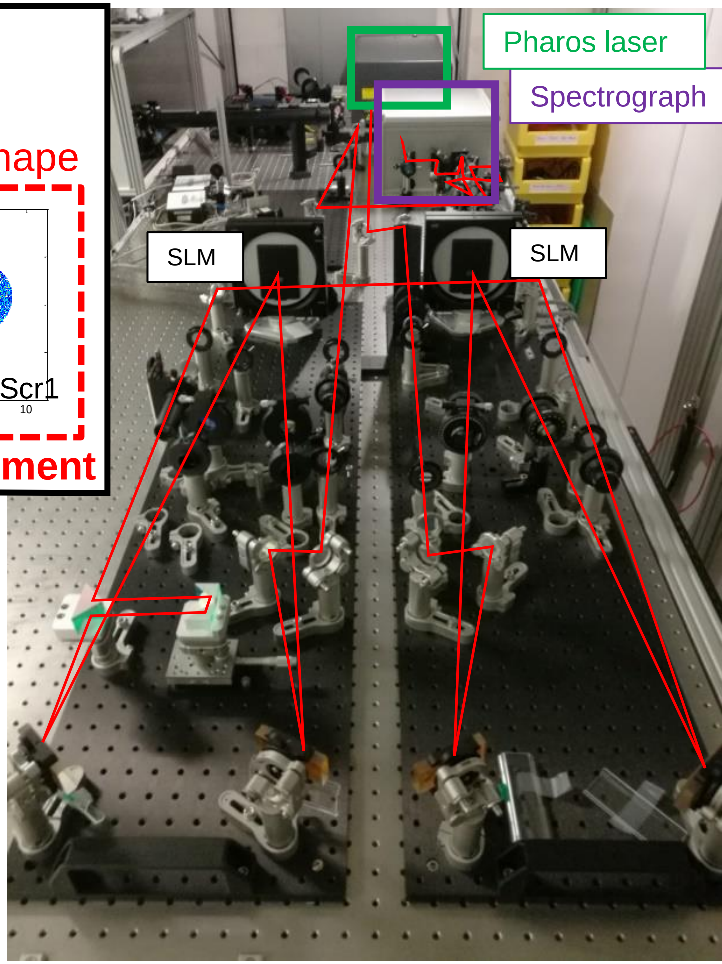
Comparison with simulated e⁻ beam shapes (500pC): similarity in shape



J. Good et al., Proc. 38th FEL Conf., WEP006 (2017)

First Measurement





Redesign to true double SLM setup based on commercial PHAROS laser:

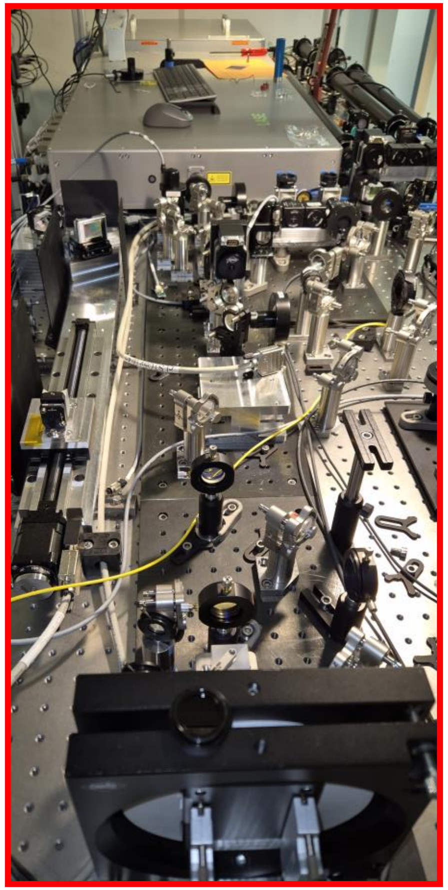
- Improved **stability**
- Improved shaping capabilities: independent masking in x and y, spectrograph feedback
- Conversion from IR to UV dilutes beam quality
  → now: shape at green wavelength

→ flexible laser shaping, backup for work horse system !

Latest development: NEPAL systems from DESY's FS-LA group

Modern development, high stability and flexibility, unifying photo cathode lasers at DESY

	FLASH	EuXFEL	PITZ
Parameter	**NEPAL-F**	**NEPAL-XD/X**	**NEPAL-P**
Burst structure	burst length: 1 ms two segments with 50-70 µs gap, each segment has different pulse parameters	burst length: 1 ms two segments with 50-70 µs gap, each segment has different pulse parameters	burst length: 1 ms
Intra-burst repetition rate	40 kHz, 50 kHz, 100 kHz, 125kHz, 200kHz, 250 kHz, 500 kHz, 1 MHz	100 kHz, 254 kHz, 564 kHz, 1.125 MHz, **2.25 MHz**, **4.5 MHz**	40 kHz, 50 kHz, 100 kHz, 125kHz, 200kHz, 250 kHz, 500 kHz, 1 MHz **4.5 MHz**
Wavelength	257 nm	257 nm	257 nm
Pulse energy for long pulse	10 µJ	**5 µJ**	**10 µJ (1 MHz), 5 µJ (4.5 MHz)**
Longitudinal pulse shape, long pulse	Gaussian, up to 14 ps FWHM Option for 20 ps flat-top with 1ps from 10-90% rising edges	Gaussian, up to 14 ps FWHM Option for 20 ps flat-top with 1ps from 10-90% rising edges	Gaussian, up to 14 ps FWHM Option for 20 ps flat-top with 1ps from 10-90% rising edges
Pulse energy for short pulse	5 µJ		**5 µJ (1 MHz and 4.5 MHz)**
Longitudinal pulse shape, short pulse	Gaussian, < 1 ps FWHM		Gaussian, < 1 ps FWHM
Pulse-to-pulse energy stability	< 1% rms at cathode	< 1% rms at cathode	< 1% rms at cathode



2023: NEPAL-P replaced MBI laser as work horse at PITZ

Courtesy: Lutz Winkelmann, Ingmar Hartel

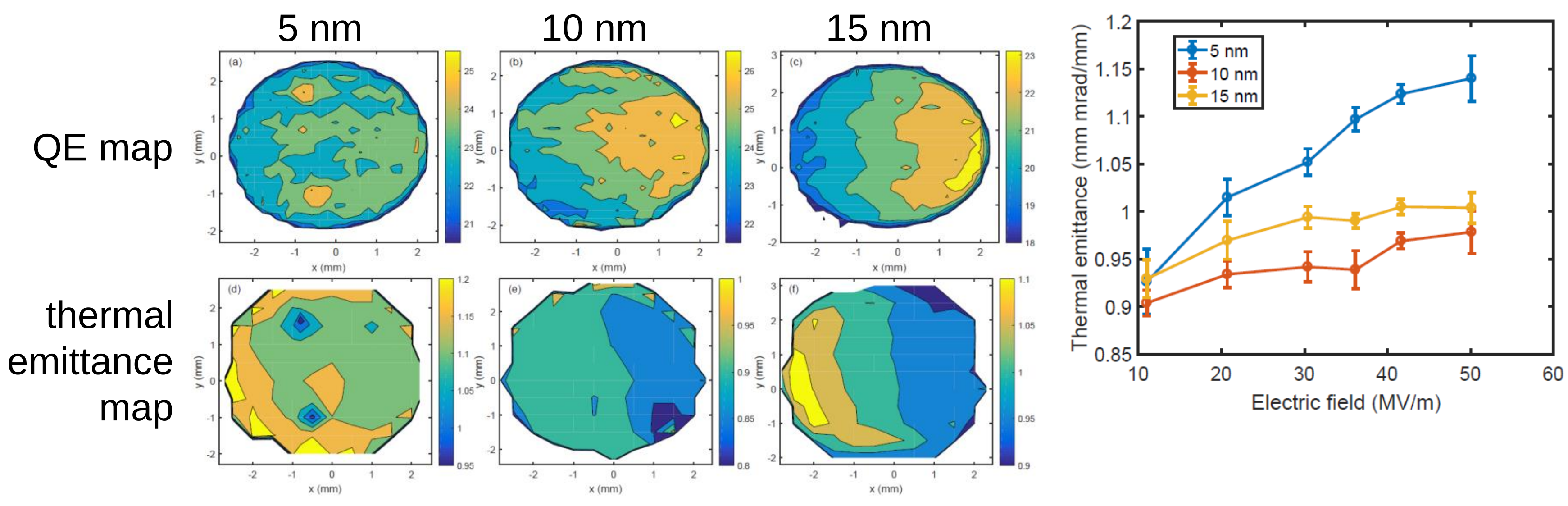
Photo cathode developments

Photo cathode developments

Mainly UV cathodes (Cs_2Te) were used at PITZ, INFN LASA Milano also develops green cathodes

Cs2Te:

- Developments for DESY machines for were done by **INFN LASA Milano**
- Standard production for DESY (EuXFEL, 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

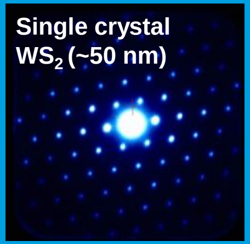
→ PRAB **25**, 053401 (2022)

Green cathodes:

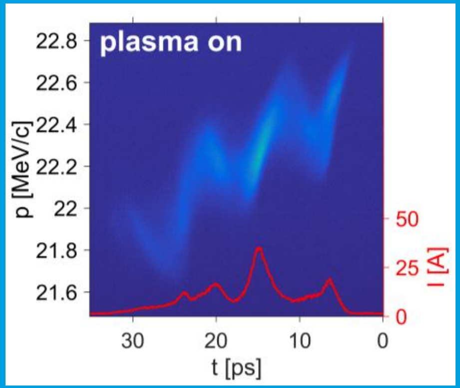
- Emission at **green** photo cathode (PC) laser **wavelength**
- Goals:
  - √ **Lower thermal emittance**
  - √ **Quick response time**
  - √ **Simplified PC laser system** → no UV conversion → simplified laser shaping, less laser power
- Requirements:
  - Low **dark current**,
  - Long **life time**
  - High **robustness**
- First tests at PITZ done, developments continues …

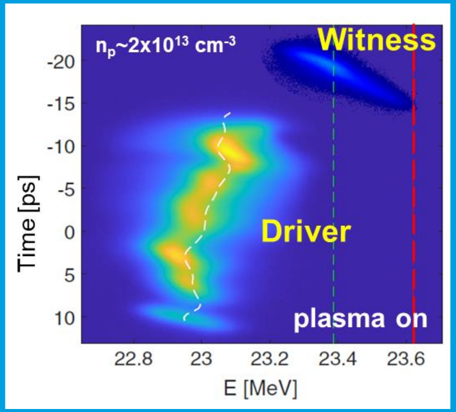
Applications of high brightness electron sources:

- Ultrafast electron diffraction

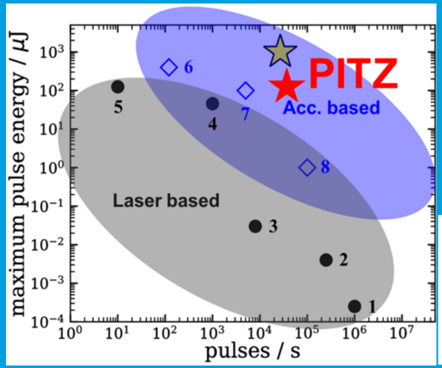


- Beam driven plasma acceleration: self-modulation & high transformer ratio





- Bunch microstrucre generation with DLWs
- Highest power, tuneable THz source



1,3-5: Optical rectification[1]
2: photoconductive antenna [1]
6: CTR (LCLS/FACET) [2]
7: UR (FLASH) [3]
8: UR (TELBE) [4]

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

- FLASH radiation therapy and radiation biology

One application of high brightness electron sources beyond FELs:

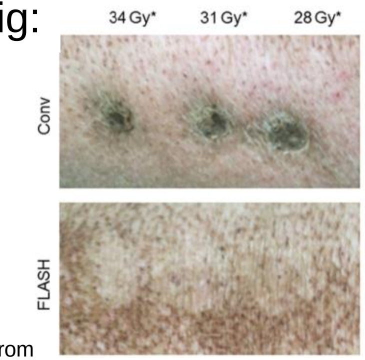
FLASH radiation therapy and radiation biology

FLASH radiation therapy (FLASH RT) for cancer treatment

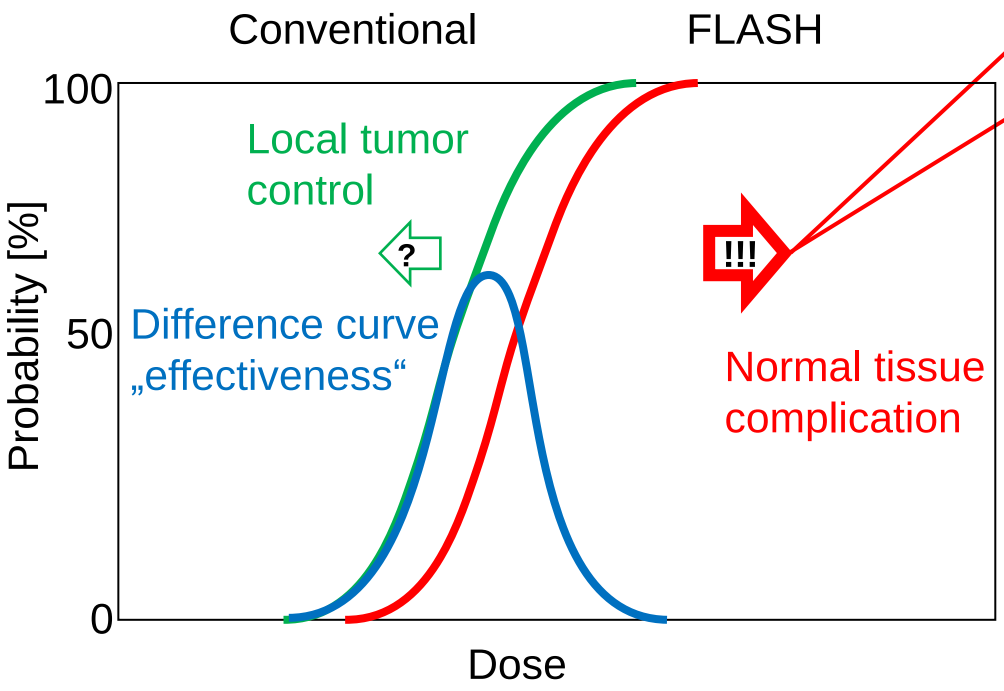
FLASH effect is an experimental observation (Favaudon, 2014), underlying mechanism still under study

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

Mini-pig:



from
Clin Cancer Res (2019) 25 (1): 35–42.



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

→ **Opening therapeutic window**

→ **Strongly reduce treatment time (e.g. 5 weeks → 1 msec !!!), simplify life for patients + reduce costs**

→ **Treating radiation resistant cancer**

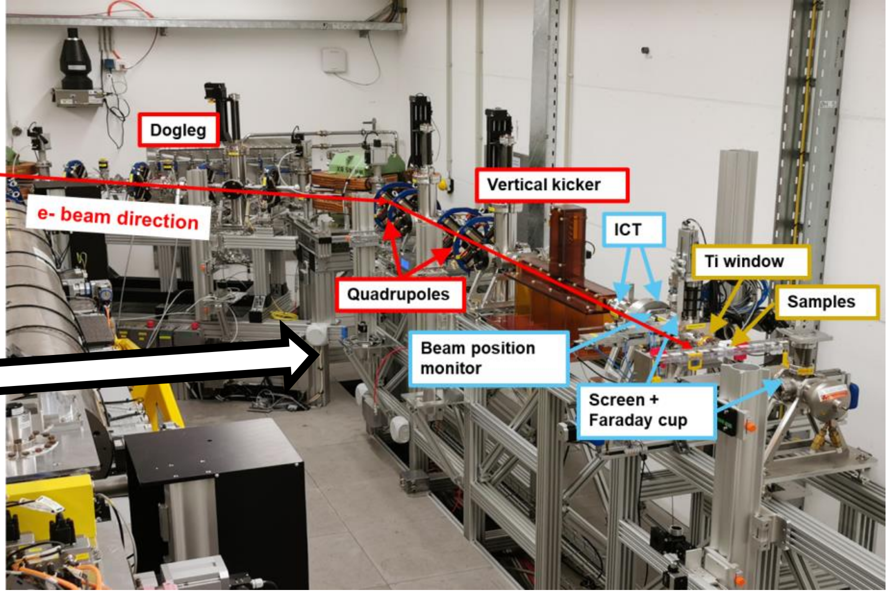
Key Questions:

- **How does the FLASH effect work ?**
- **How to optimize it for the benefit of cancer patients ?**

Fairly new activity: → FLASH*lab*@PITZ

Use existing accelerator and know how for high impact in society

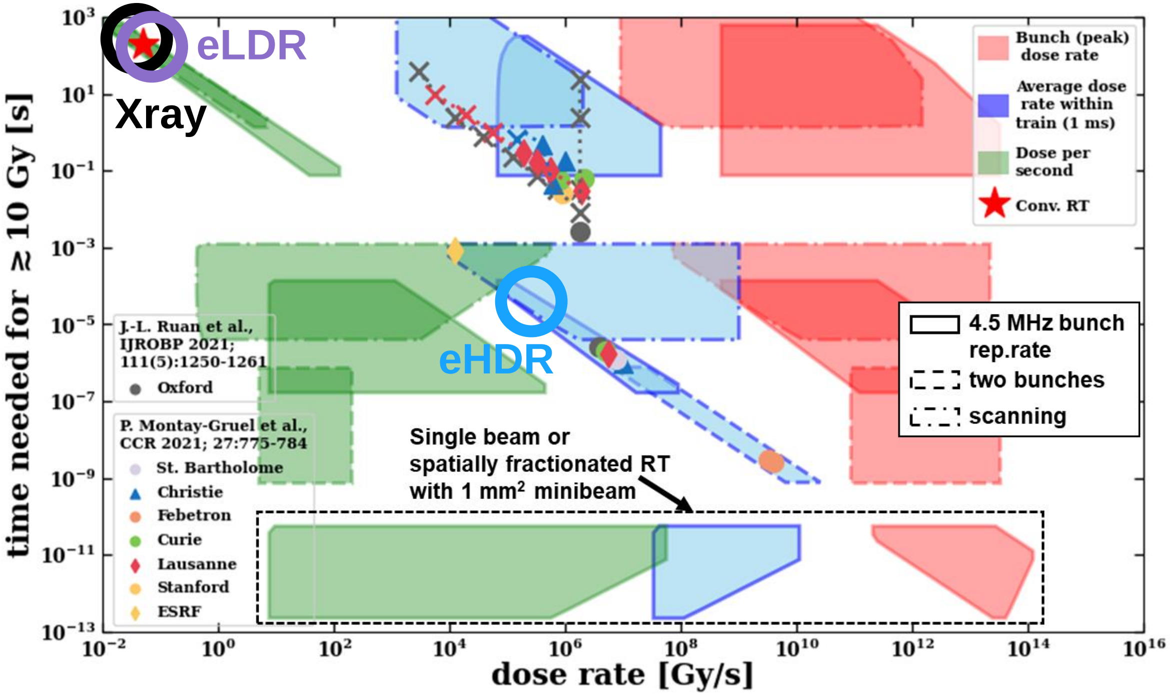
→ advance cancer treatment

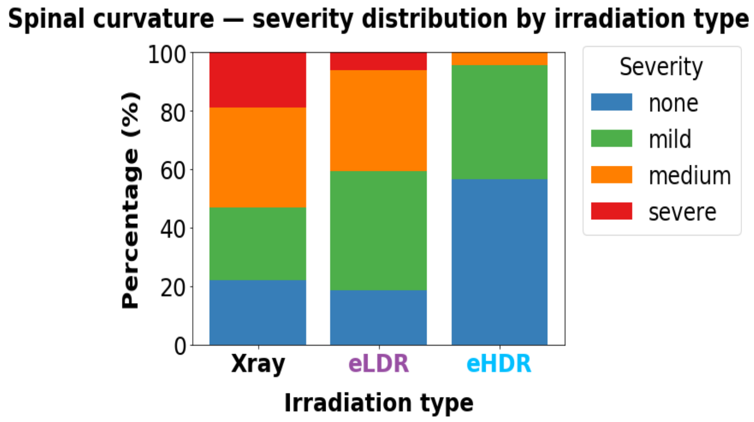


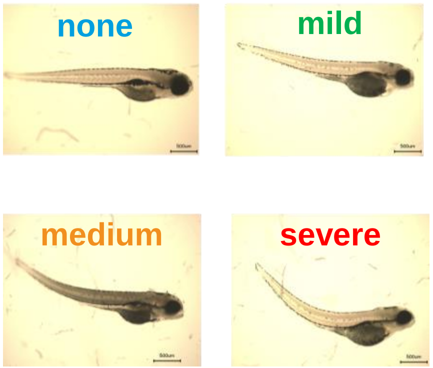
- **Biolab + dedicated beamline** was put into operation

- PITZ can provide a worldwide uniquely wide parameter range to **systematically study and optimize the FLASH effect** for the benefit of cancer patients

- Besides many *in vitro* experiments also **first successful *in vivo* experiments** with zebrafish embryos
  → **sparing of healthy tissue** demonstrated !







Conclusion

In a strong collaboration MUCH can be achieved.

Sincere thanks to all collaboration partners since >25 years.