20 years of photo electrons at the Photo Injector Test facility at DESY in Zeuthen (PITZ): High brightness electron sources and their applications

Frank Stephan for the PITZ collaboration

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Sincere **thanks** to all **cooperation partners** helping to make PITZ a success !

PITZ Photo Injector Test Facility Zeuthen

DESY.

Outline of the talk

high brightness electrons sources for X-ray FELs → beam driven plasma acceleration
→ first high power THz SASE FEL
→ cancer therapy

Why the talk now ?

I) Photo injector developments for high brightness beams to drive X-ray FELs:

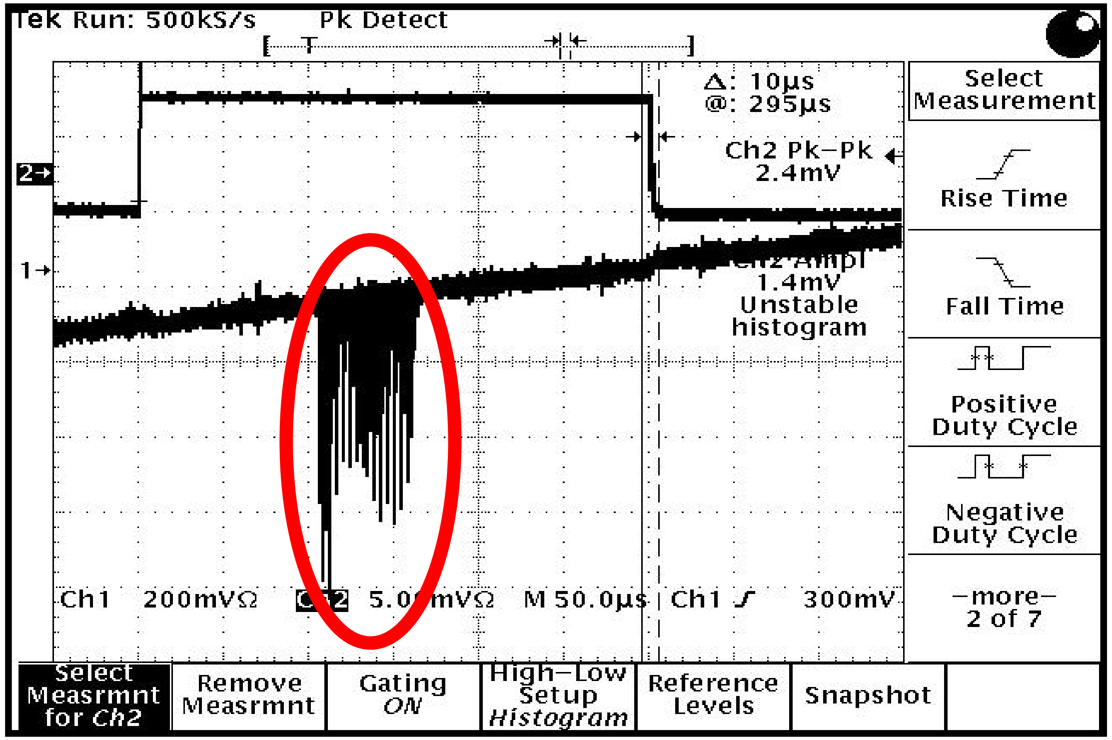
- Why PITZ was started
- R&D for high brightness beams: a) progress on emittance reduction,
  b) summary of gun developments
  c) photo cathode laser developments
  d) photo cathode developments

II) Other high brightness beam applications:

- Tests towards UED studies
- R&D on beam driven **plasma acceleration**: a) experimentally proving self-modulation instability
  b) high transformer ratio measurements
- Generating beam modulations via dielectric lined waveguides
- **THz SASE FEL**
- **FLASH radiation therapy** and radiation biology

20 Years ago: Start of beam operation at PITZ

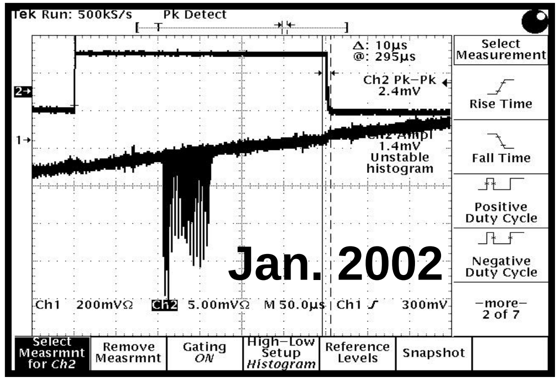
January 13th, 2002:
First photo electrons at PITZ

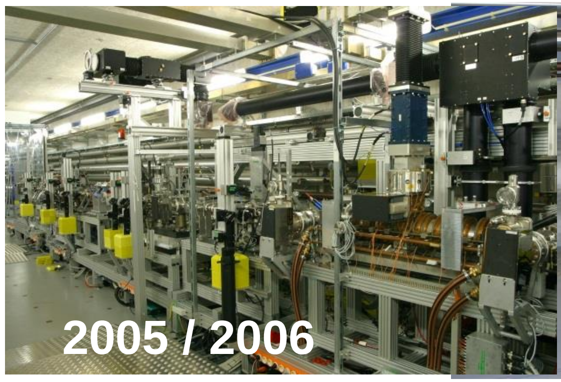


Official start on 30.1.2002: Prof. Wagner and Prof. Wanka open the photo cathode laser shutter during the colloquium „10 years DESY in Zeuthen"

Early history of PITZ

- Q1/1999: request to BMBF to build gun test facilty independant 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





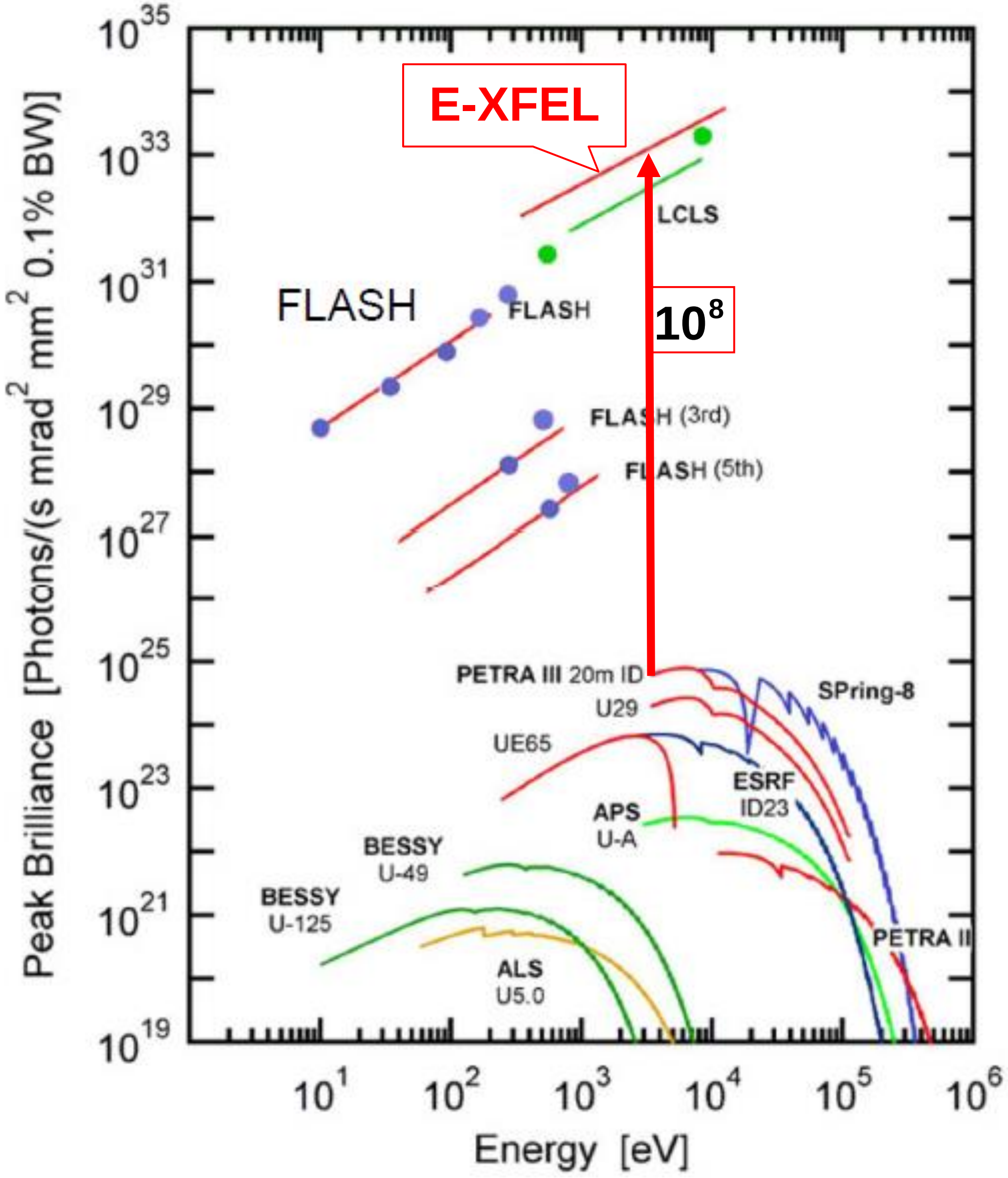
Why PITZ was started ?

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

European XFEL - a next generation light source with unique capabilities

Discussion ~20 years ago, still true:

- 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):

$$P \sim (N \cdot e)^2 = N^2 \cdot e^2 ,$$
$$N \sim 10E+8$$

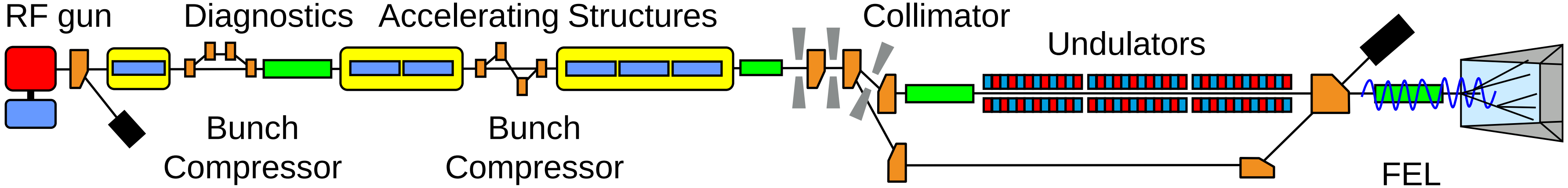
XFEL key component: → high brightness electron source

Why electron injector is so important …. ???

➔ property of linacs: beam quality will DEGRATE 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

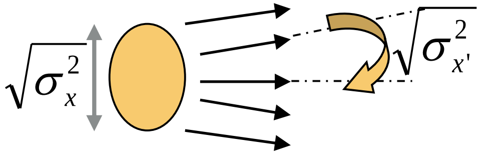
} increase normalized transverse emittance

Emittance – a measure of the beam quality

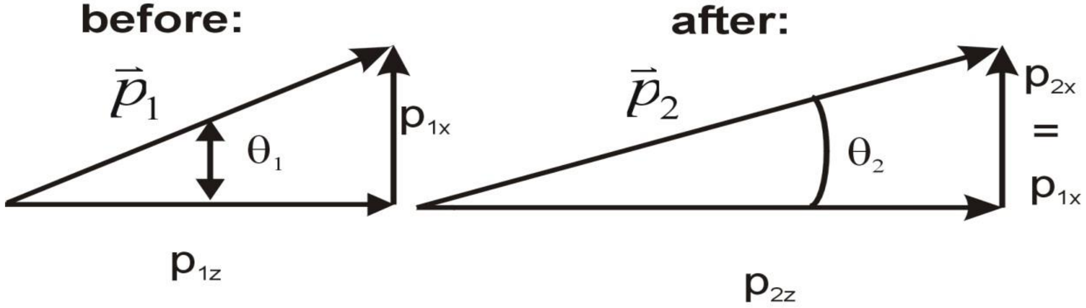
ε = 6 dimensional phase space volume occupied by given number of particles

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

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

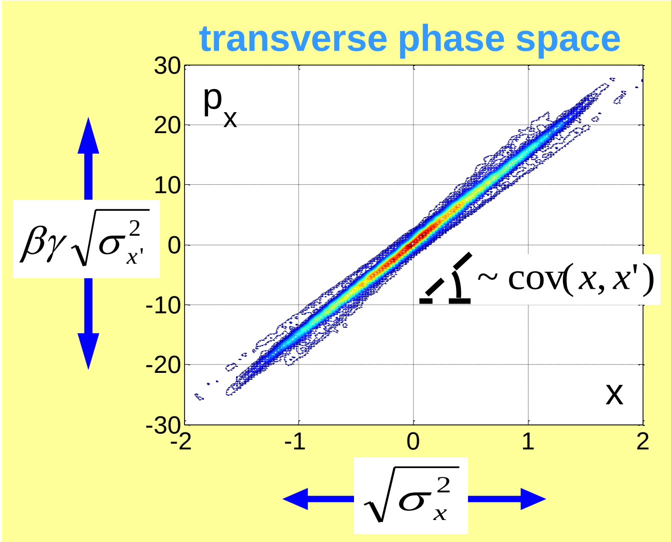


effect of <u>acceleration</u> on transverse emittance (adiabatic damping):



$\theta_2 < \theta_1$

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



⇒ 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)

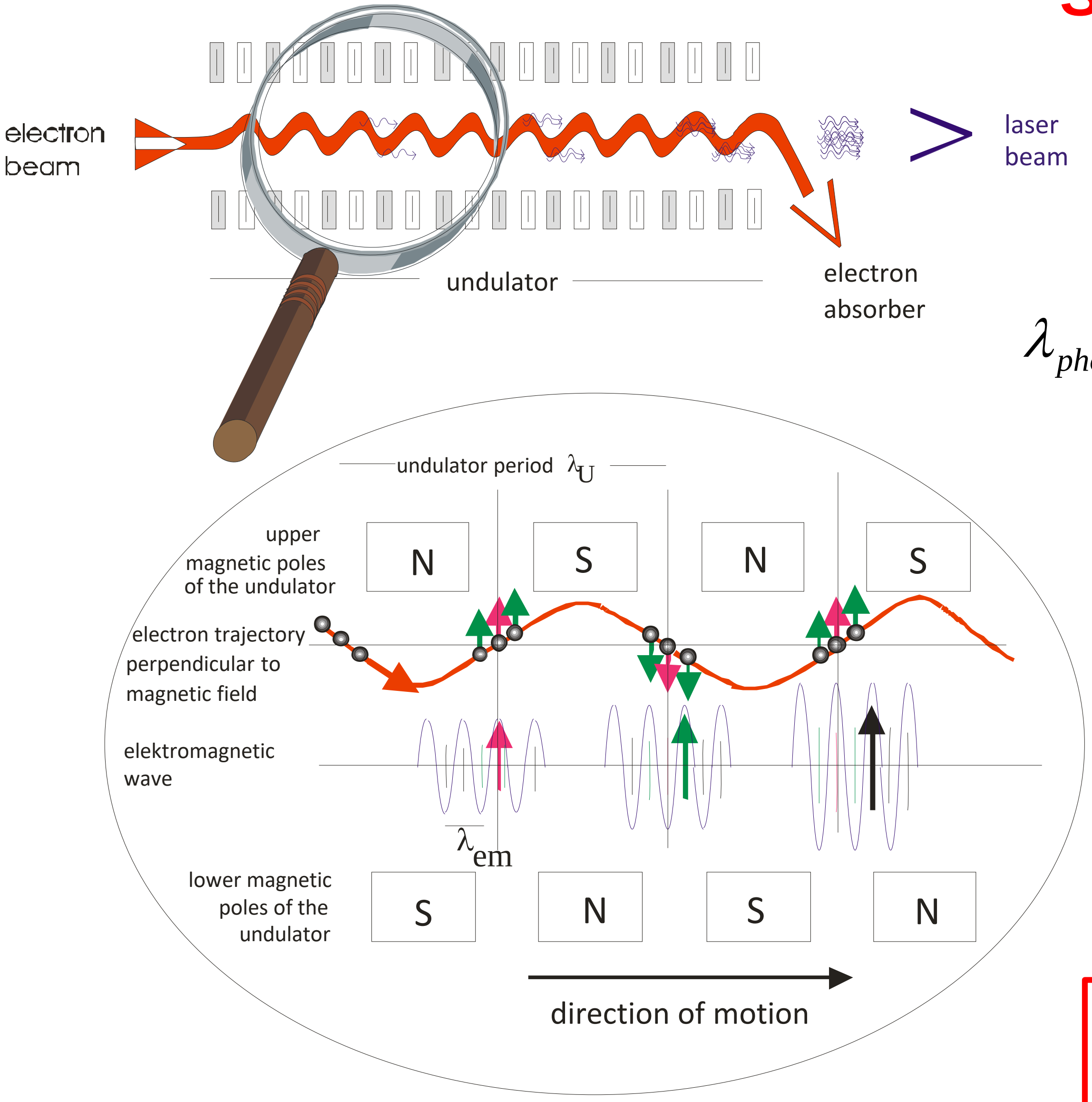
SASE FEL: How does it work?

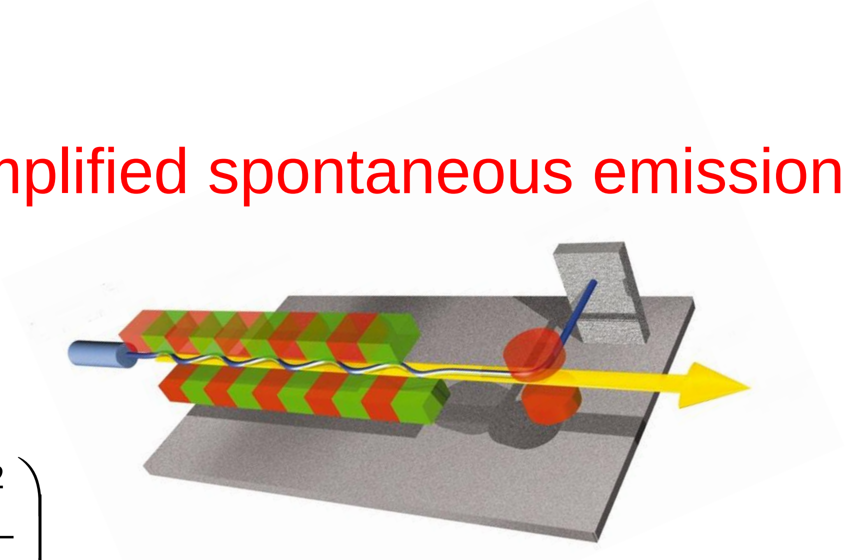
Coherent motion is all we need !!

Courtesy: Jörg Rossbach

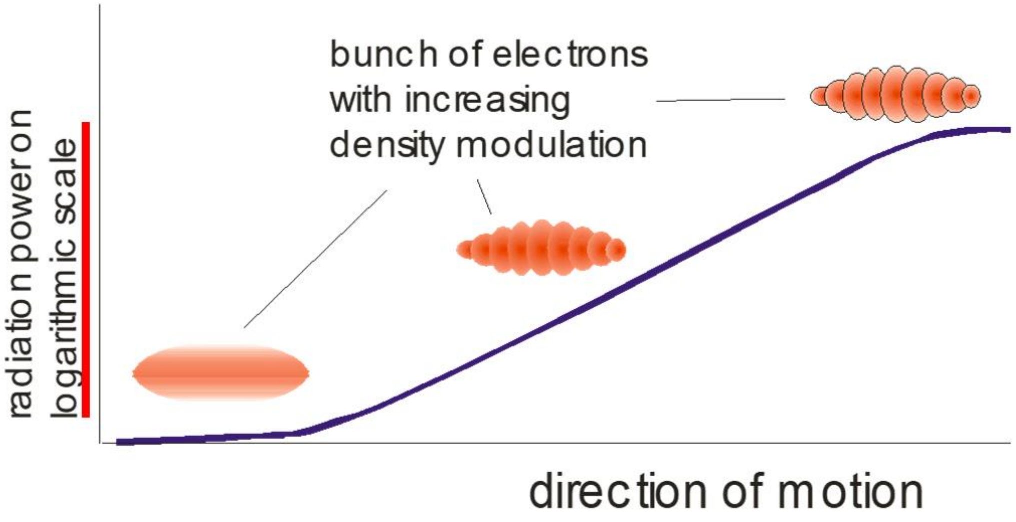
SASE FEL: How does it work?

SASE = self amplified spontaneous emission





$$\lambda_{photon} = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$



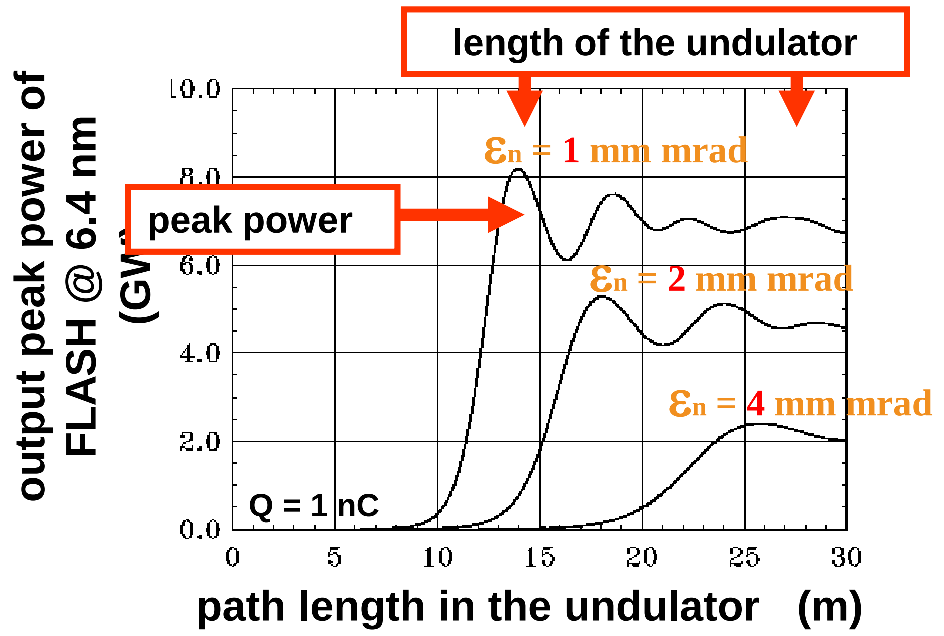
$$\lambda_{min}[\text{nm}] \approx \frac{4\pi}{10}\frac{\varepsilon_n[\text{mm mrad}]}{\sqrt{I_p[\text{kA}]\cdot L_u[\text{m}]}}$$

Courtesy: Jörg Rossbach

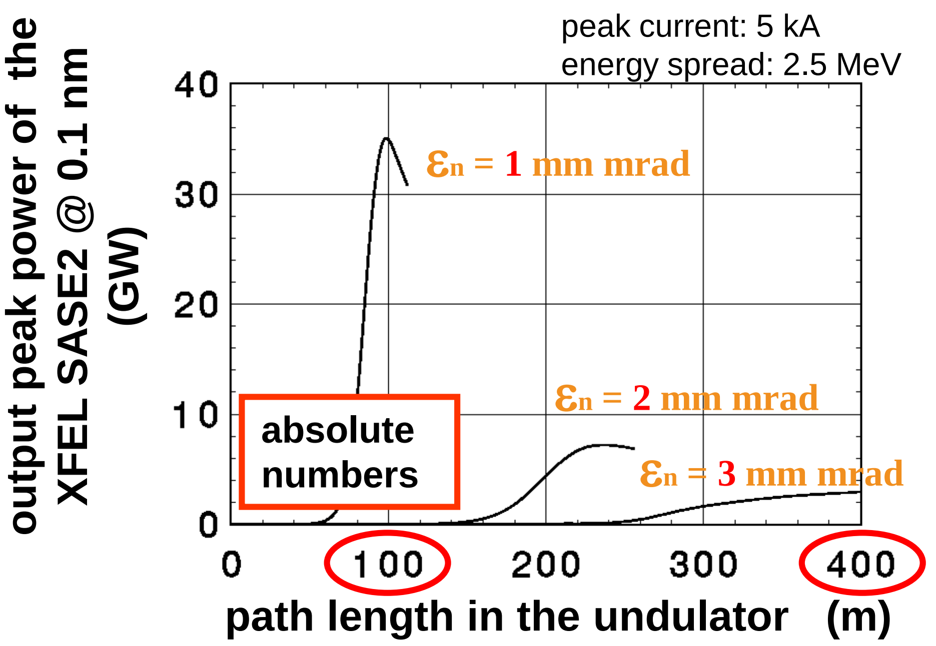
Why emittance must be small …

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

FLASH



XFEL

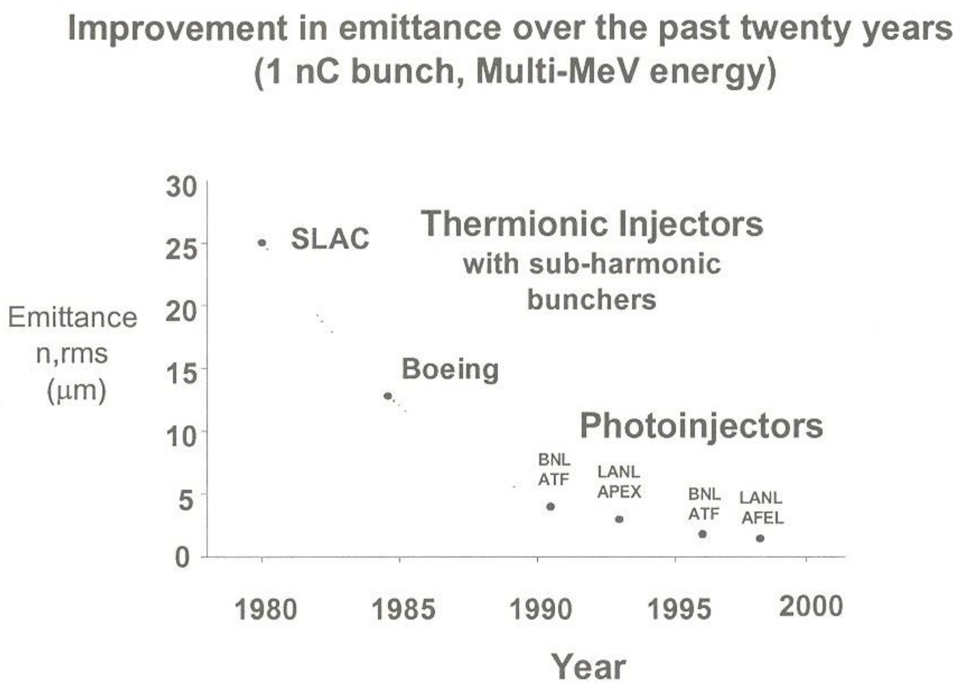


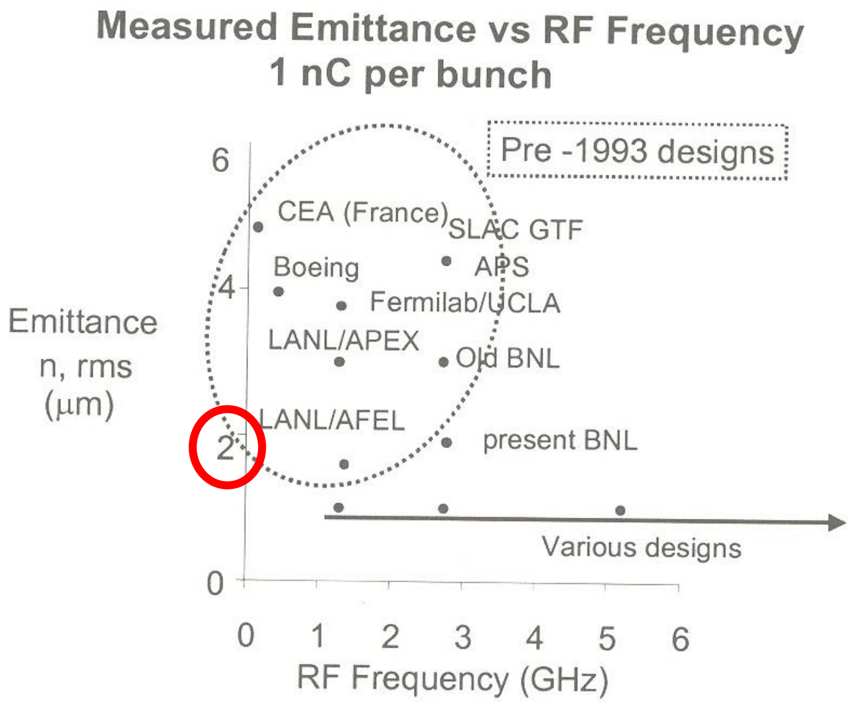
- **original XFEL goal: 0.9 mm mrad@injector = 1.4 mm mrad@undulator**
- **if even smaller emittance ⇒ shorter wavelength, higher repetition rate**

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:



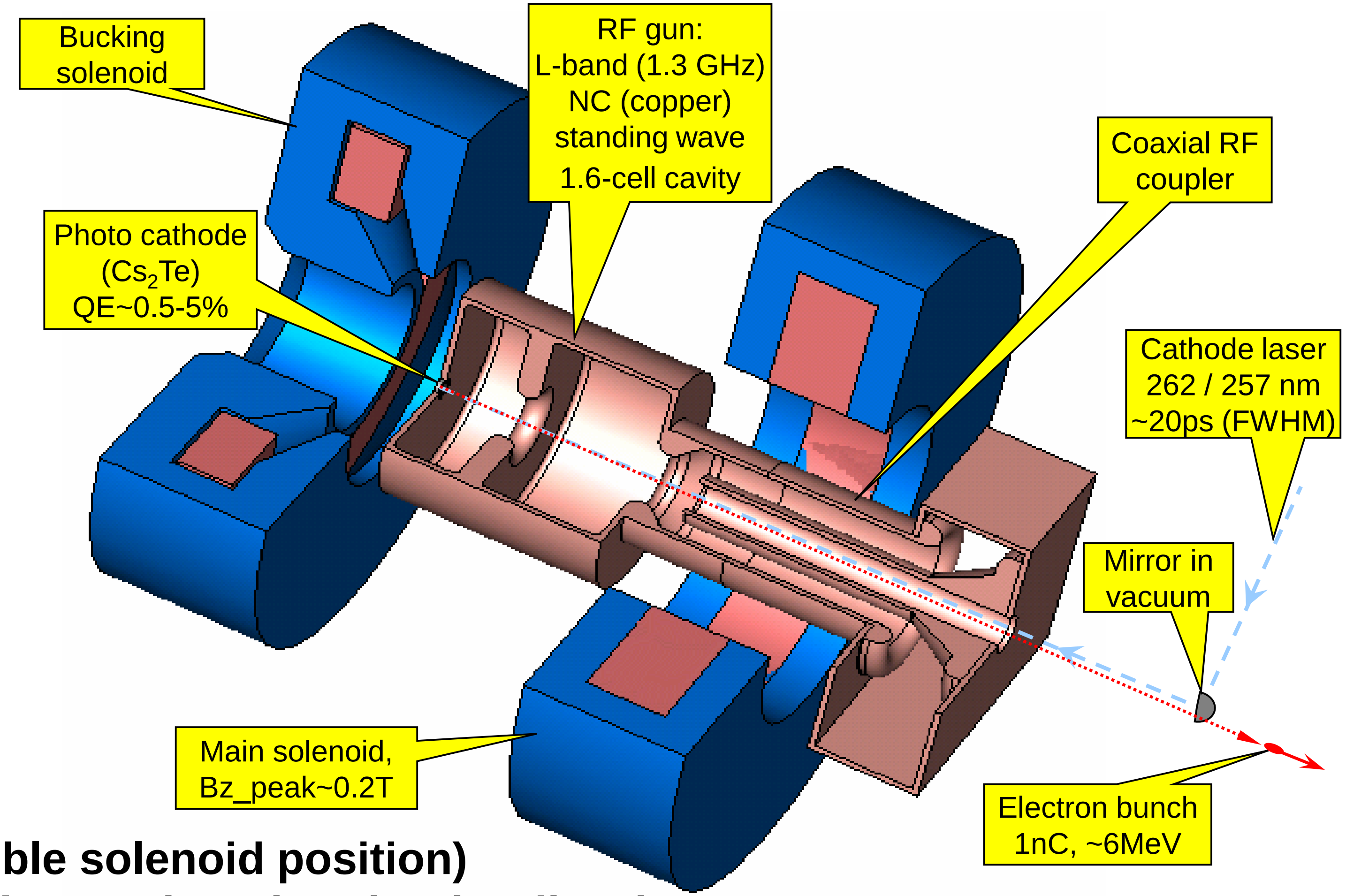


"Goal for community in next years:

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

Most prominent solution to solve low emittance problem:
Photo Cathode RF Gun

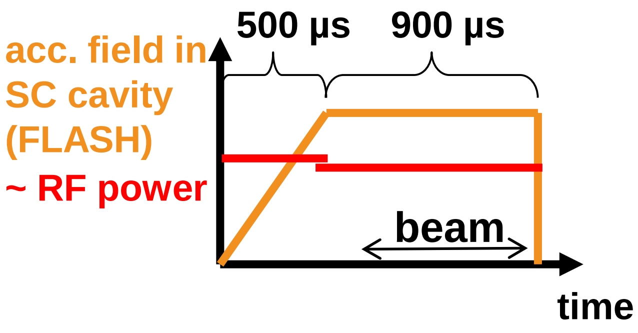
Example: PITZ gun

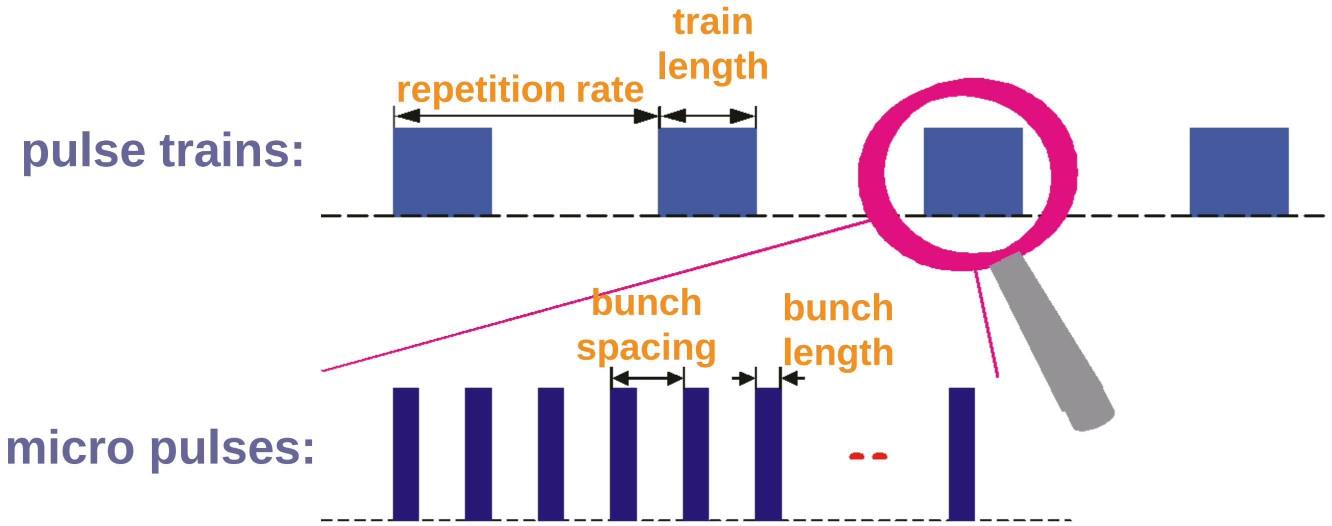


Main properties of PITZ gun:
1.3 GHz cavity, coaxial RF coupler (flexible solenoid position)
Capable of high average power → long electron bunch trains (SC linac)
Very low normalized transverse emittance

Some parameters of FLASH and European XFEL

A pulsed SC linac needs long bunch trains to run efficiently





Parameters	FLASH	European XFEL
final beam energy	1.2 GeV	17.5 GeV
max. repetition rate	10 Hz	10 Hz
max. train length	800 µs	650 µs
bunch spacing	1 – 20 µs	0.2 – 1 µs
required injector emittance (1 nC)	2 mm mrad	0.9 mm mrad
SASE output wavelength	4 – 90 nm	0.05 – 4.7 nm

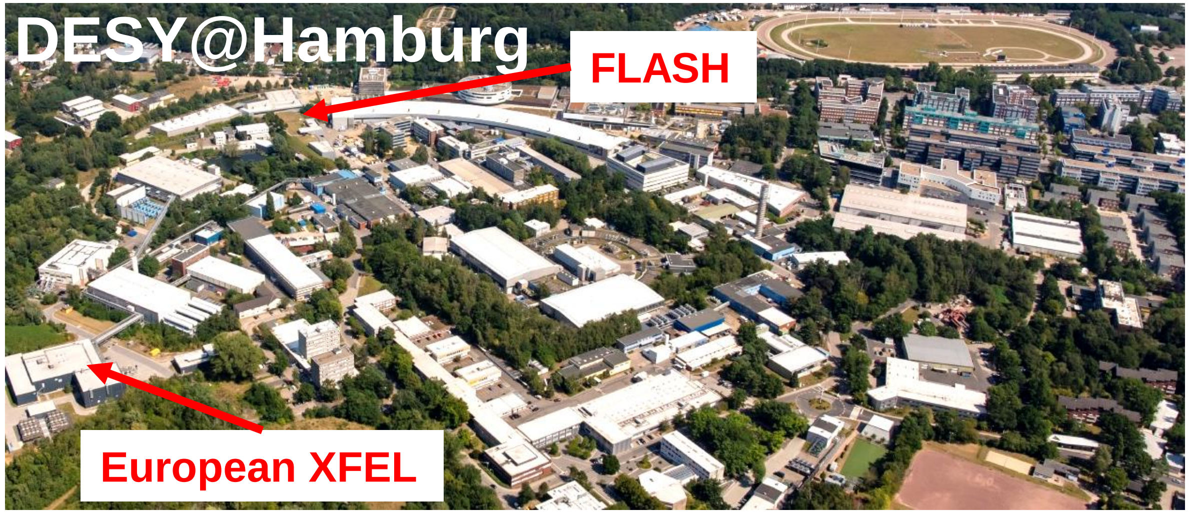
→ Gun 5 aims for 1ms !

DESY

Largest accelerator center in Germany, one lab - two locations: Hamburg + Zeuthen (near Berlin)

Facts and Figures

- publicly funded national research centre of the Helmholtz Association
- **Employees** at DESY
  - approximately **2700**, including 1180 scientists
- Interdisciplinary research, international cooperation
- Research at DESY in 4 areas:
  - **Accelerators**
  - Photon Science (focus in Hamburg)
  - Particle Physics
  - Astroparticle Physics (focus in Zeuthen)

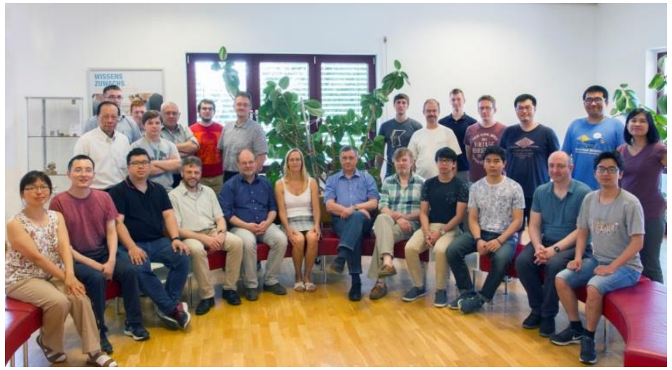


Courtesy: Ulrike Behrens

PITZ Collaboration Partners (formal contract signed)

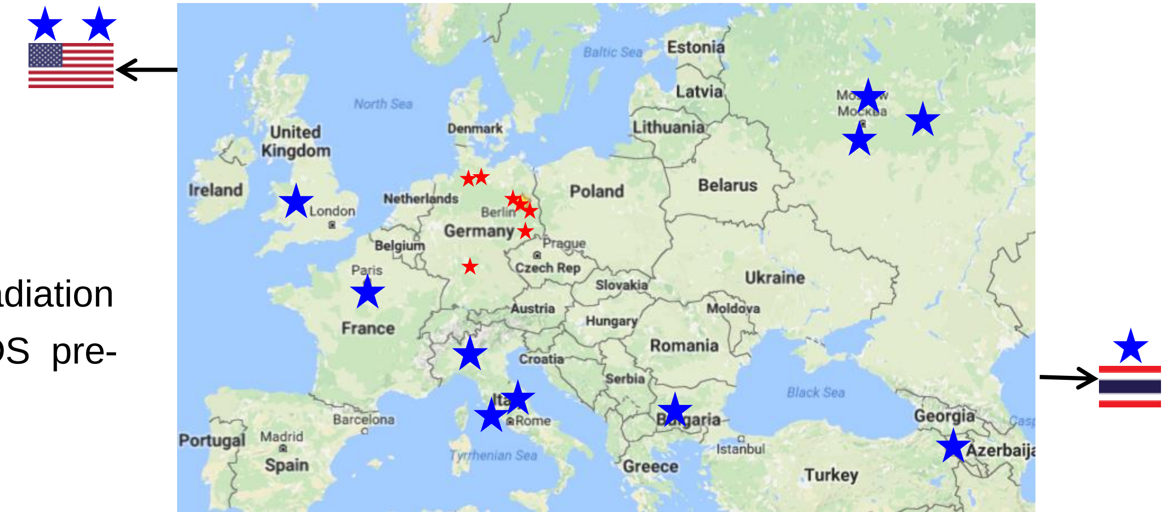
contract on **green** photocathodes

- **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

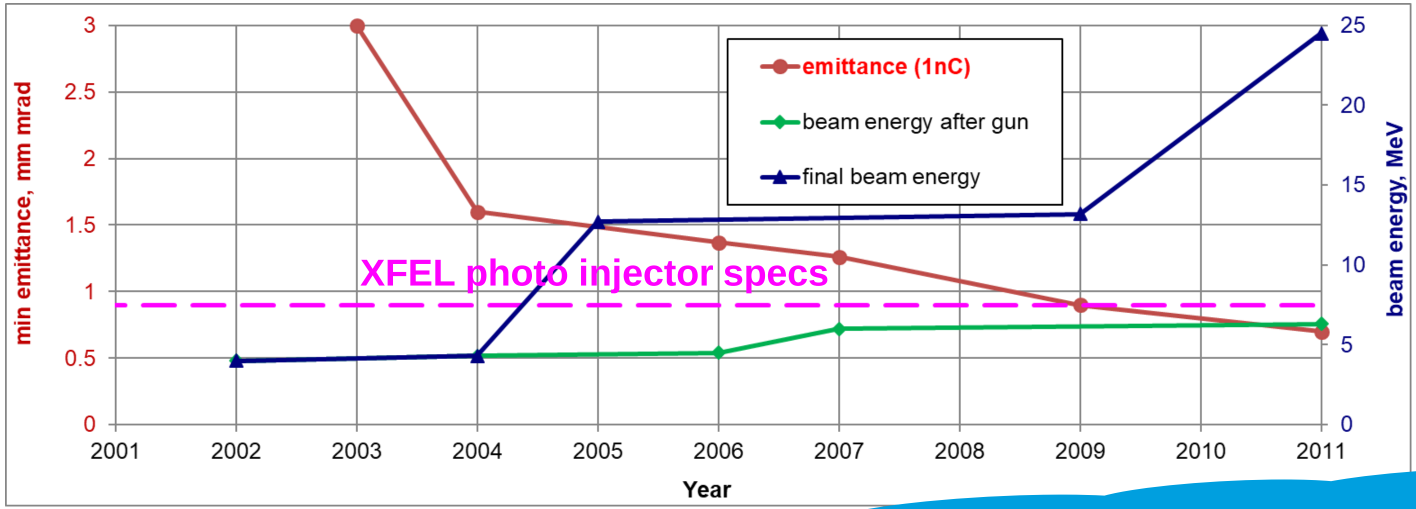
- **International partners:**
  - Currently suspended → **IAP Nizhny Novgorod + JINR Dubna**: 3D elliptical laser pulses, THz radiation
  - **INFN Frascati + Uni Roma II** (M. Ferrario, L. Palumbo): E-meter and TDS pre-studies
  - **INFN Milano** (C. Pagani): photocathodes
  - Currently suspended → **INR Troitsk** (L. Kravchuk): CDS, TDS, Gun5
  - **INRNE Sofia** (D. Tonev, G. Asova): EMSY + personnel
  - **IJCLab Orsay** (S. Bousson): HEDA1 + HEDA2
  - **UKRI Daresbury** (D. Angal-Kalinin, B. Militsyn): phase space tomography
  - **Thailand Center of Excellence in Physics** (T. Vilaithong, Ch. Thongbai): personnel
  - **AANL (YERPHI)** (G. Karyan) **+ CANDLE** (B. Grigoryan), **Yerevan**: personnel
  - **LBNL Berkeley** (Th. Schenkel): PWFA, NC CW Gun
  - **SLAC** (N. Holtkamp): LCLS-I undulators



PITZ results on high brightness beams

PITZ evolution 2002 – 2022, 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
gun	cavity	Gun2		Gun1		Gun3.1	G3.2	Gun4.2		Gun4.1		G3.1	4.3	4.4	Gun4.2	Gun4.6		4.5	Gun4.2			Gun5.1
	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	EMSY1	z=1.618m			z=4.3m		z=5.74m							z=5.277m								
	Ldrift	1.01m			2.334m		2.64m							3.133m								
	method	center BL	3xBLs		e-meter	11xBLs			**continuous synchronized (detailed) scan**							+slice with TDS						
	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 performance			+emittance (EXFEL startup)							
												+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 (PWFA, THz, radiation biology)

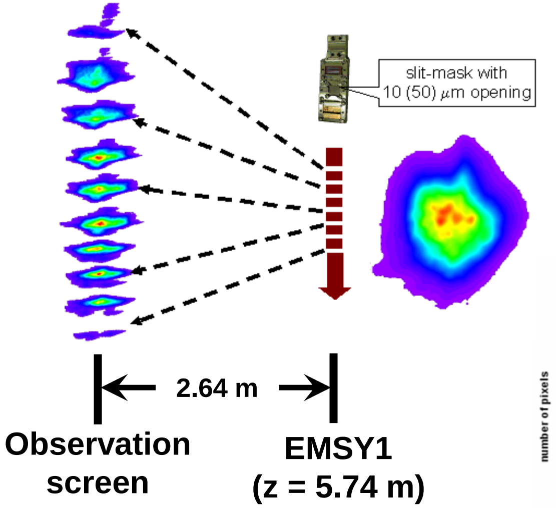
"we measure more and more of less and less…"

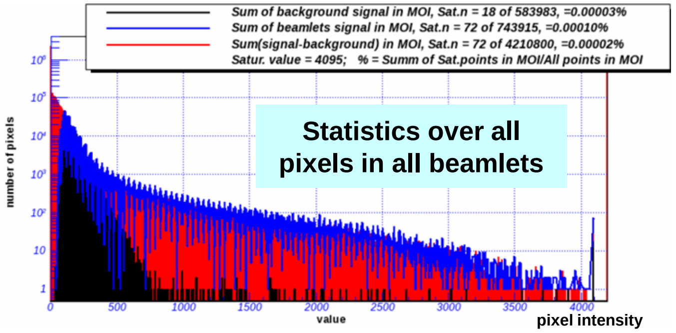
Courtesy: M. Krasilnikov

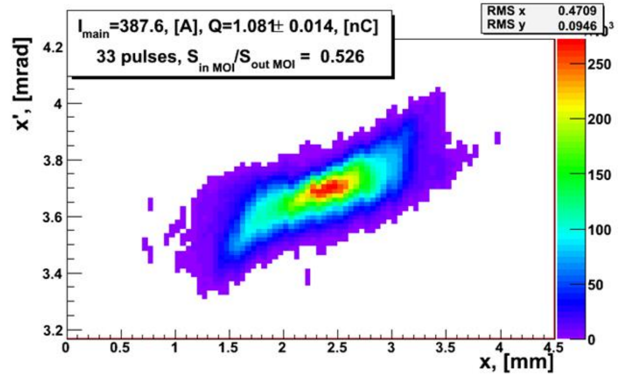
How we measure the transverse projected emittance

We primarily use the single slit scan technique

- **Emittance Measurement SYstem (EMSY)** consists of horizontal / vertical actuators with
  - **YAG** screens
  - **10** / 50 µm slits
- Beam size is measured @ slit position using screen
- Beam local divergence is estimated from beamlet sizes @ observation screen (12 bit camera)







2D corrected normalized RMS emittance

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

correction factor (>1) introduced to correct for low intensity losses from beamlet measurements

σ_x - RMS beam size measured with YAG screen at slit location

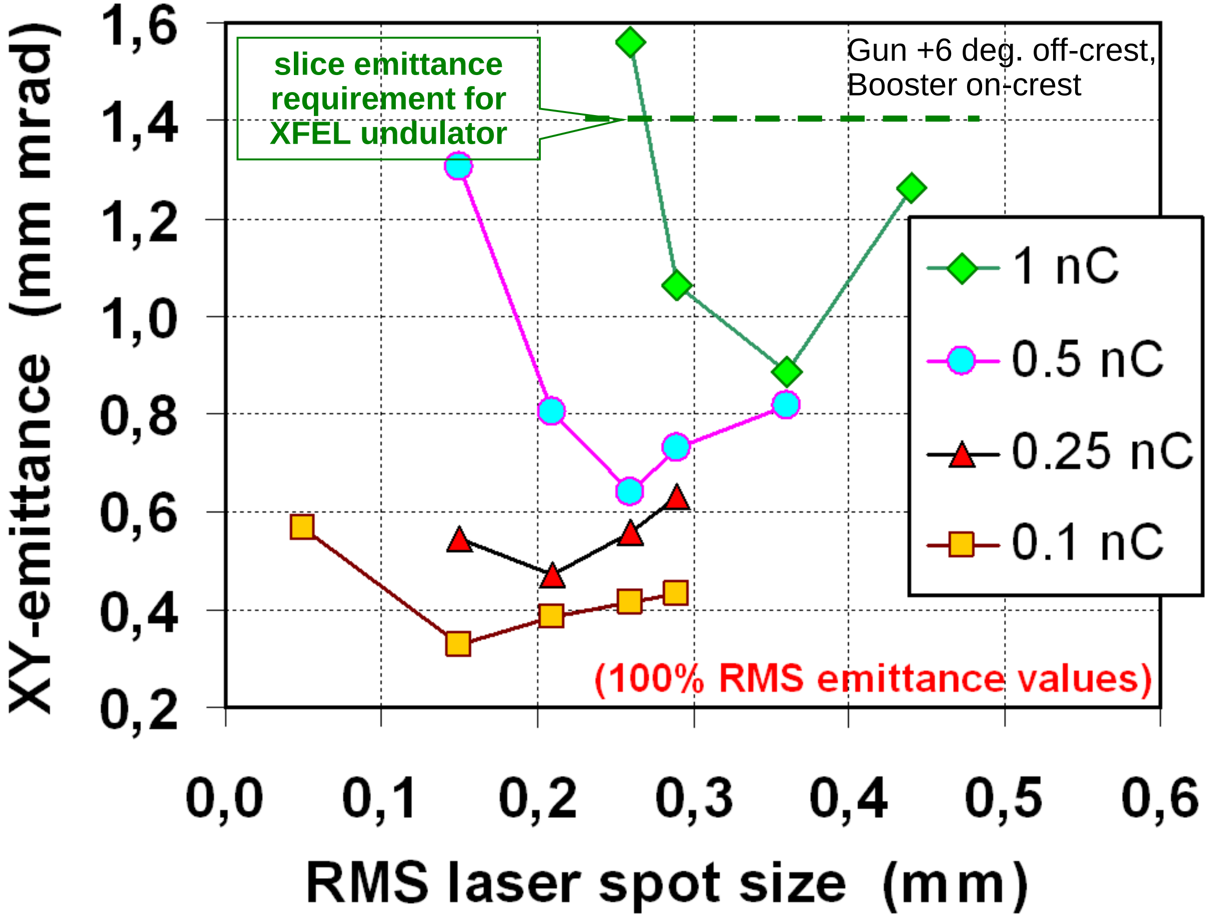
SQRT(<x^2>) - RMS beam size at slit location estimated from slit positions and beamlet intensities

➔ **"100% RMS emittance"**

Emittanz 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

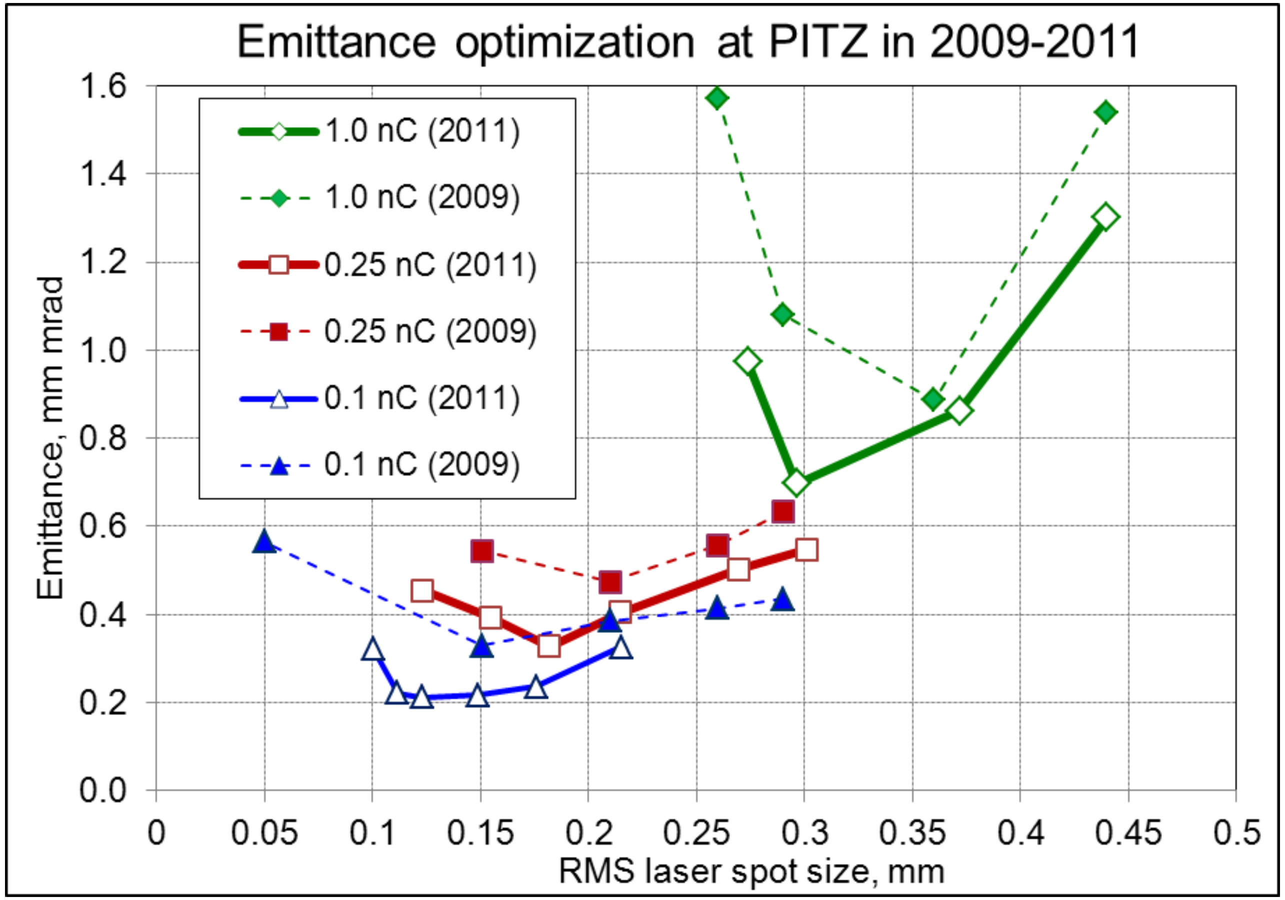


these results +
experience from LCLS
(only small degradation of slice emitt. from gun to undulator)

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

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

Emittance improvement between 2009 and 2011



Improvements:

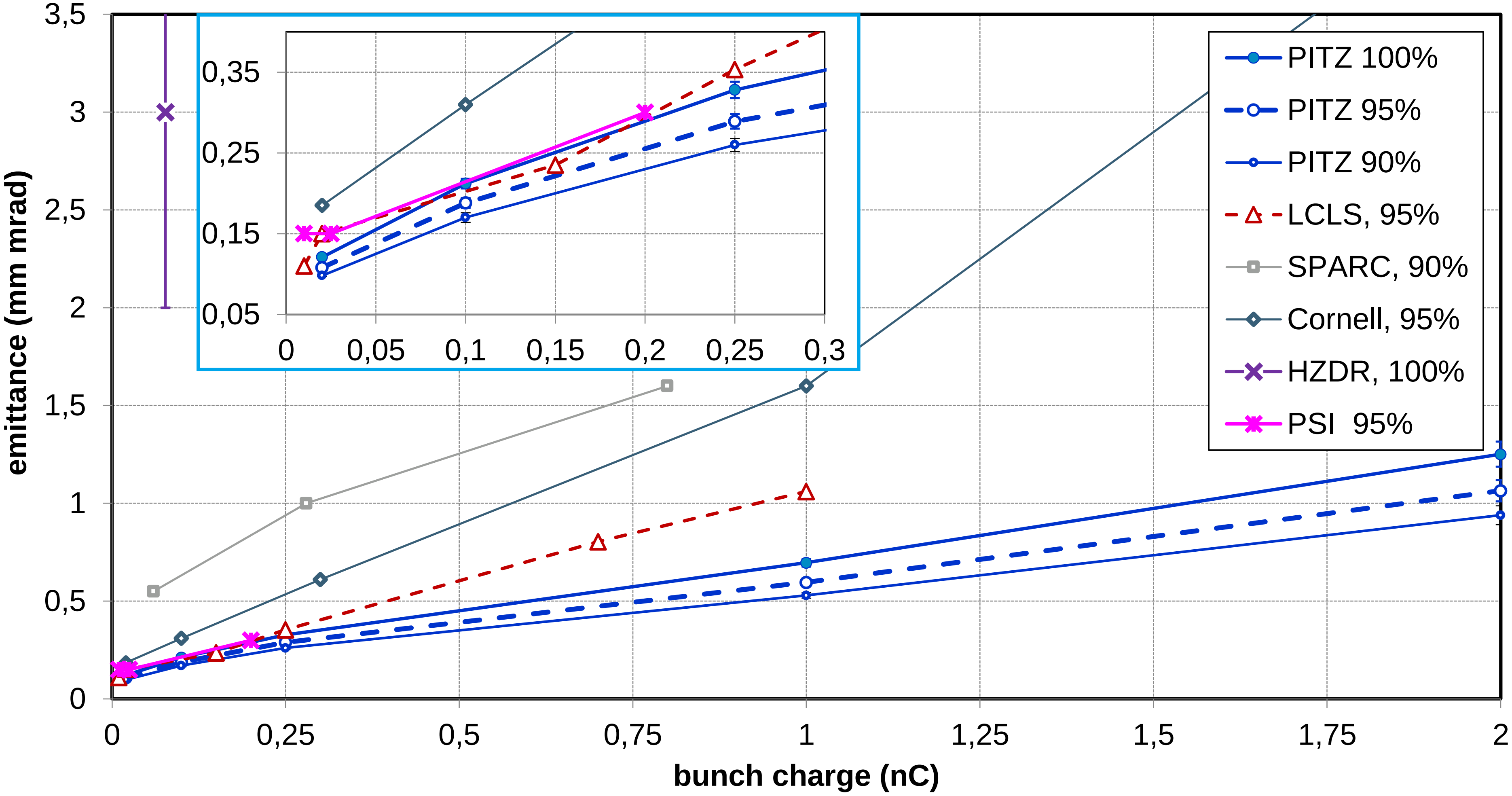
- **Gun phase stability** (10MW directional coupler + FB)
- Increased beam energy to ~25MeV (2009: <15MeV)
- Laser beam transport
- Removing magnetizable components

Q nC	ε(2011) mm mrad	δε(2011→2009) %
1.0	0.70	-20%
0.25	0.33	-30%
0.1	0.21	-35%

Higher emittance improvement for lower bunch charges due to better signal to noise ratio by using long pulse train operation

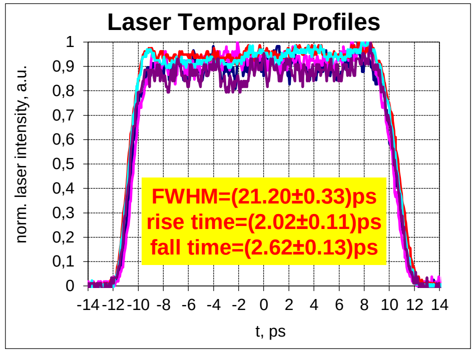
Measured RMS normalized emittance values

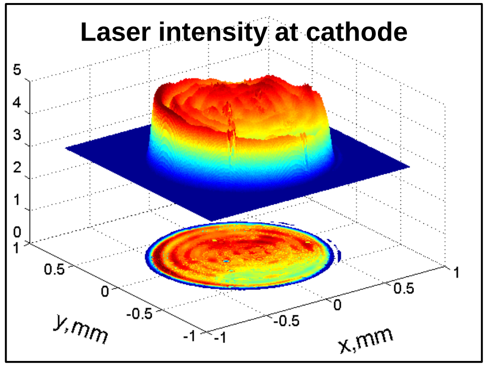
➔ PITZ world record on projected emittance from 2011 still valid



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

Photocathode laser

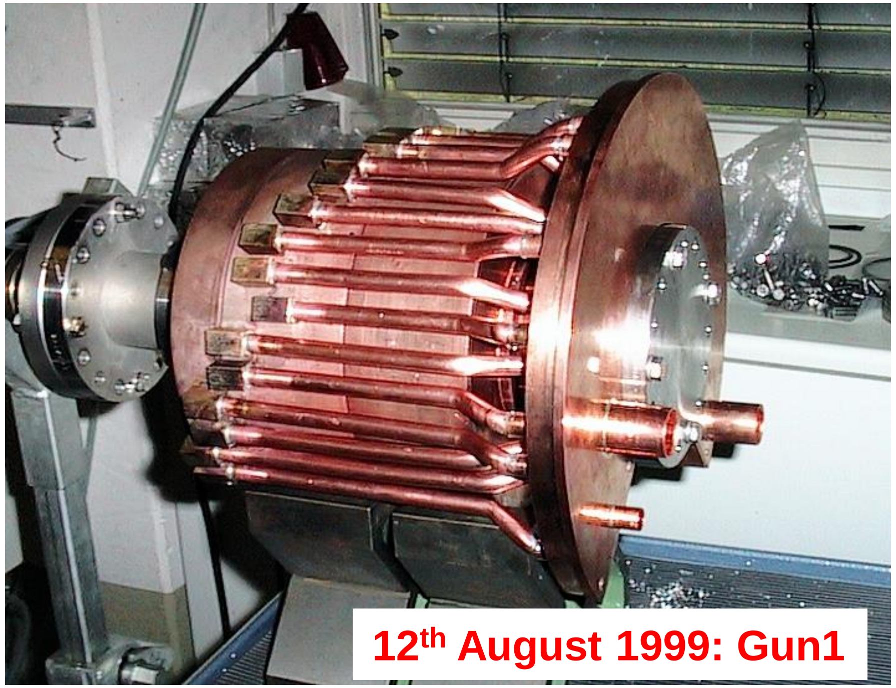




Minimum emittance measured at PITZ ($\sqrt{\varepsilon_{n,x}\varepsilon_{n,y}}$, 100%)

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

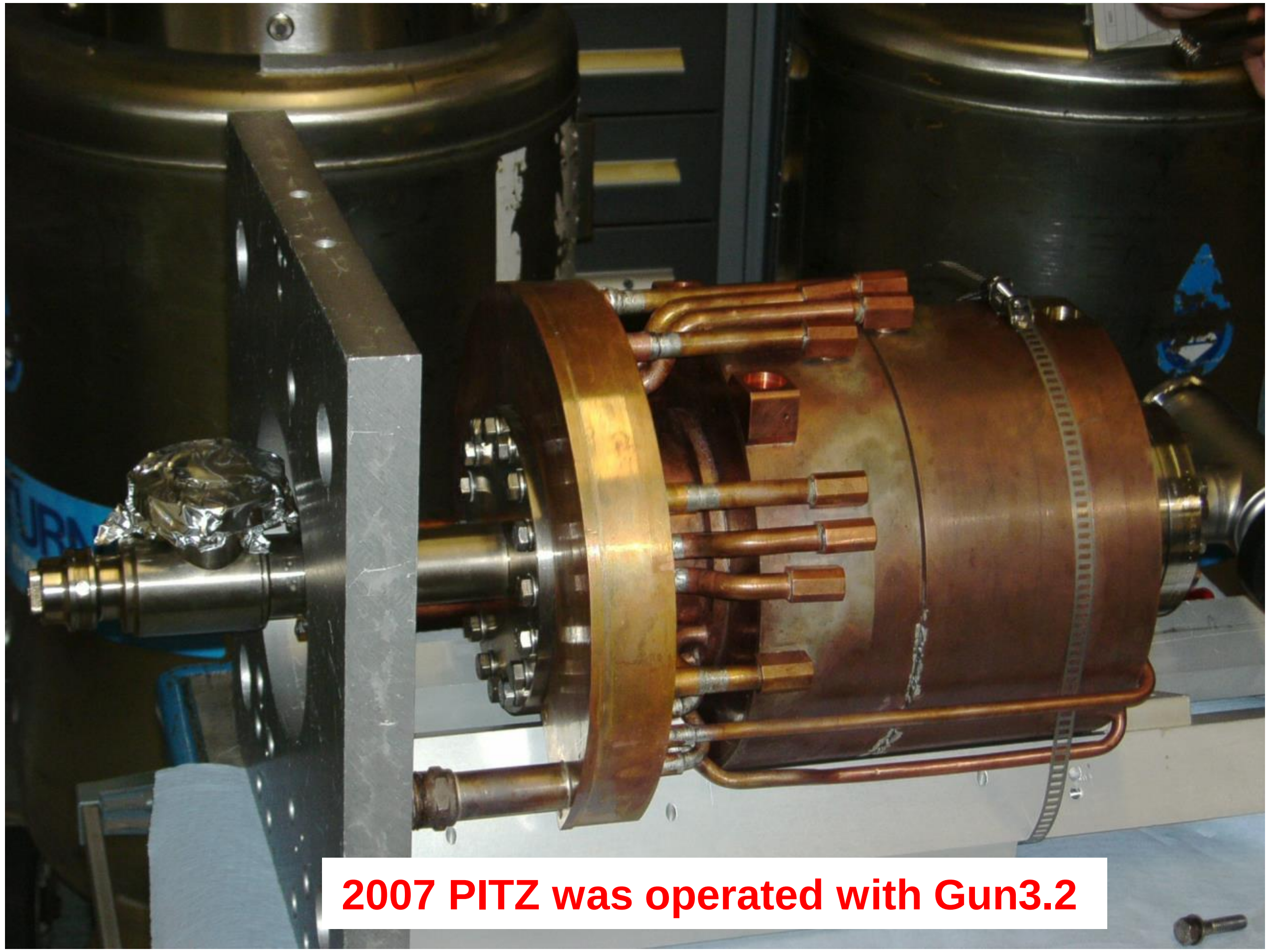
RF gun cavity developments



12th August 1999: Gun1

Modifications:

- Cooling water distribution
- Alignment capabilities
- Inner cell dimension “tuning”

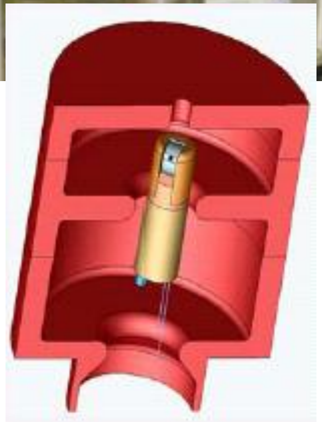


2007 PITZ was operated with Gun3.2

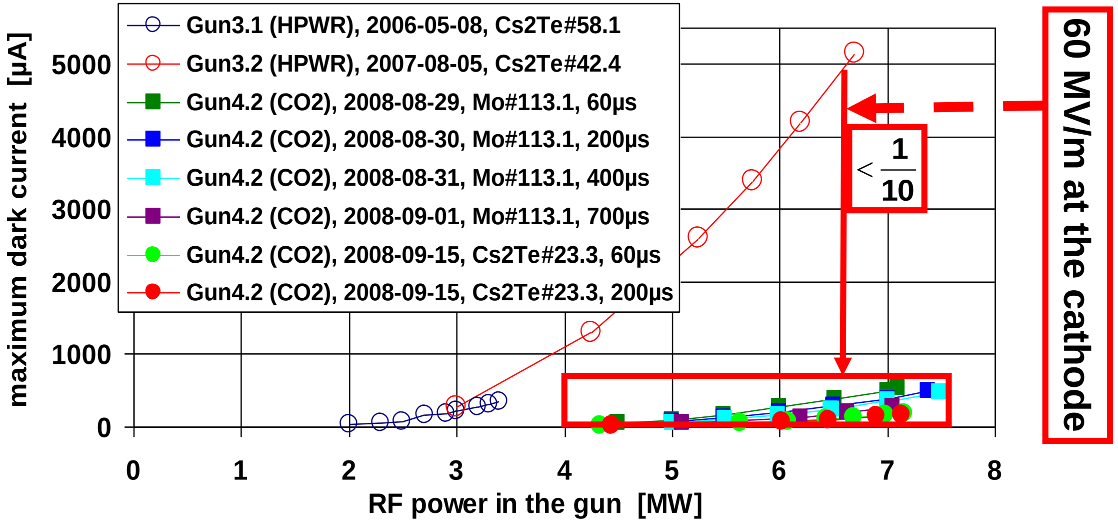
Reduction of dark current for high average power operation

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

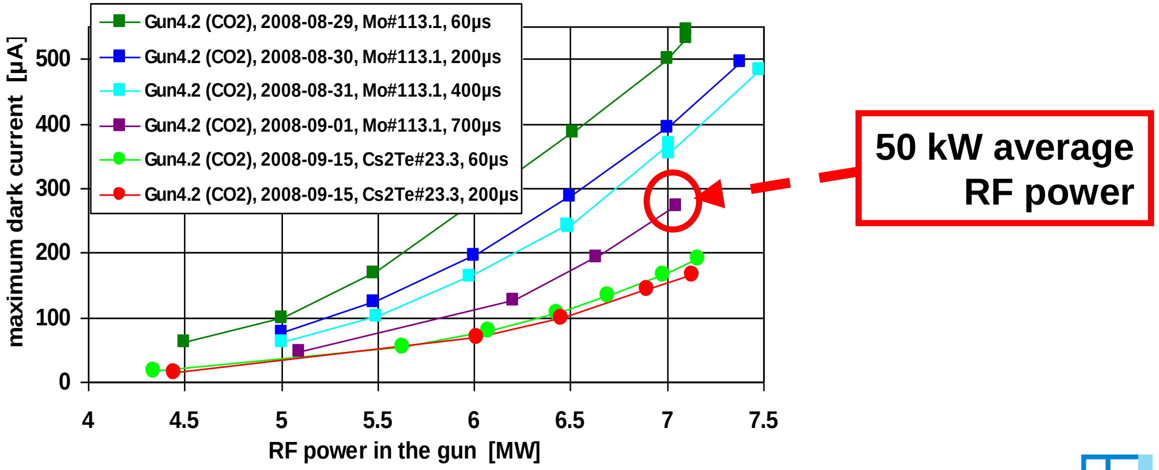
Vertical cleaning setup with 110º rotating nozzle.



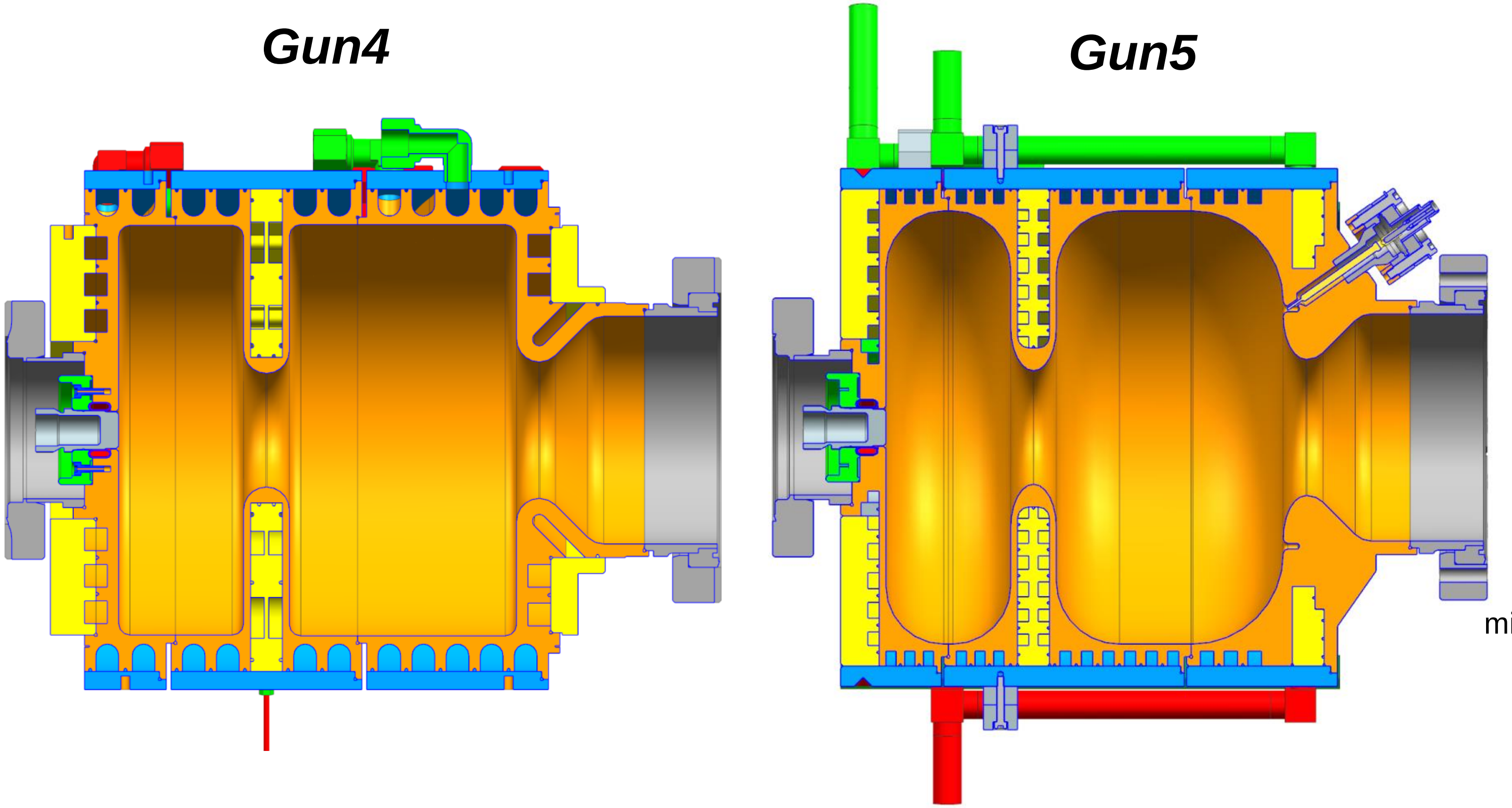
Dark current measurements

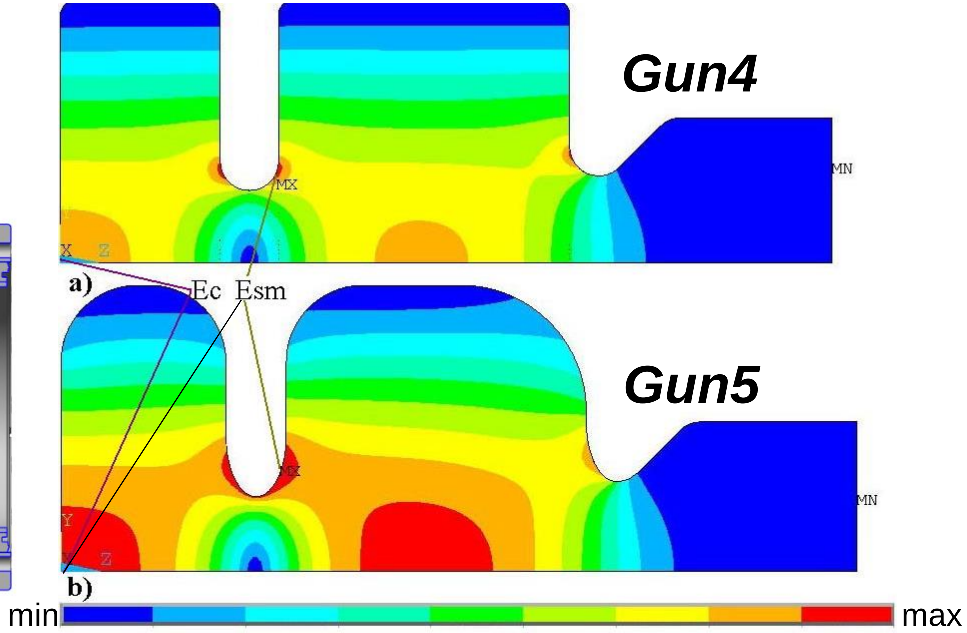


zoom:



Differences between Gun4 series and new Gun5 (latest design under test)





Electric field distribution for Gun4 (a) and Gun5 (b), from [1]

- **Optimised cell shape** for higher RF **efficiency** and reduced peak **surface field** for same cathode gradient
- Direct field measurements inside the Gun with the help of a **RF probe**
- Higher **cooling efficiency** (Gun 5: 61.3 kW average RF power, 6.13 MW for **1 ms @ 10 Hz**; from [2])

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[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

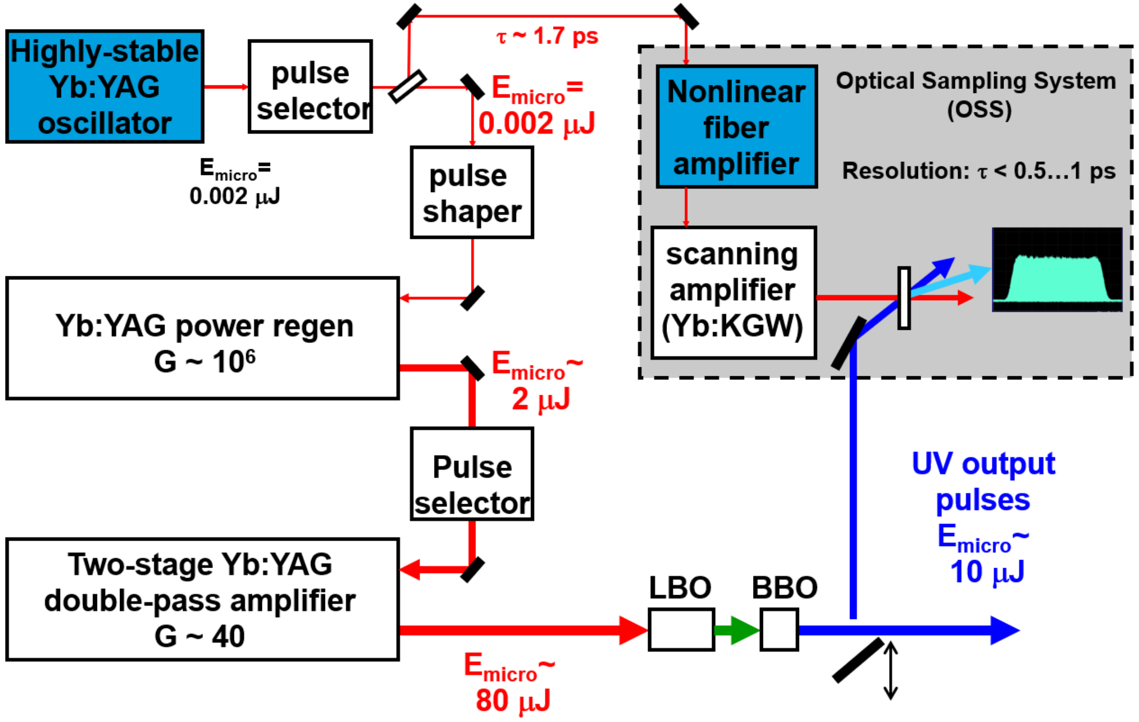
Photo cathode laser developments

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

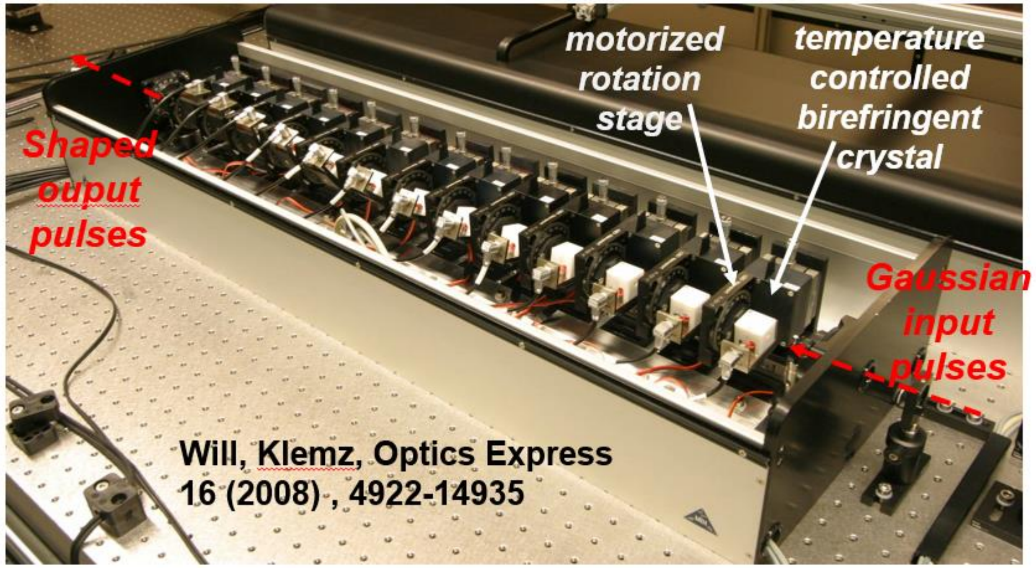
Max Born Institute, Berlin

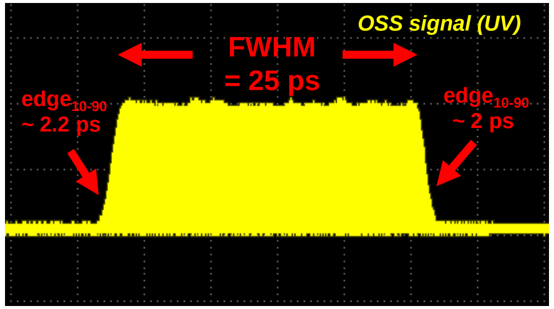
- development at MBI started 1998/99
- many intermediate steps realized + tested at PITZ
- MBI also provided other photo cathode laser systems for FLASH, European XFEL, ELBE, HZB

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

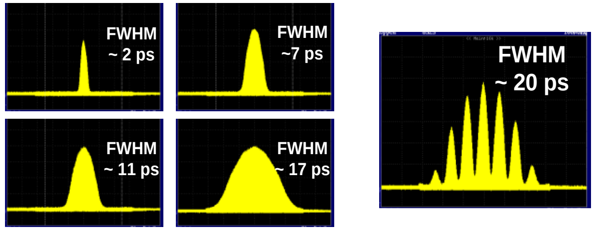


Multicrystal birefringent pulse shaper containing 13 crystals





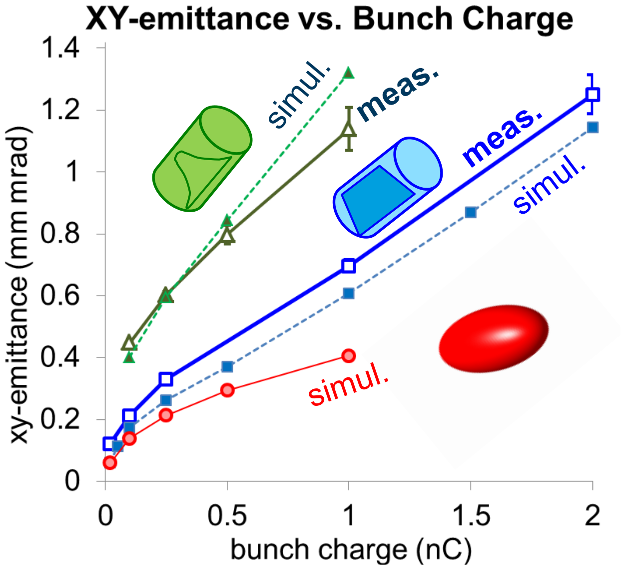
Gaussian:



→ very high flexibility

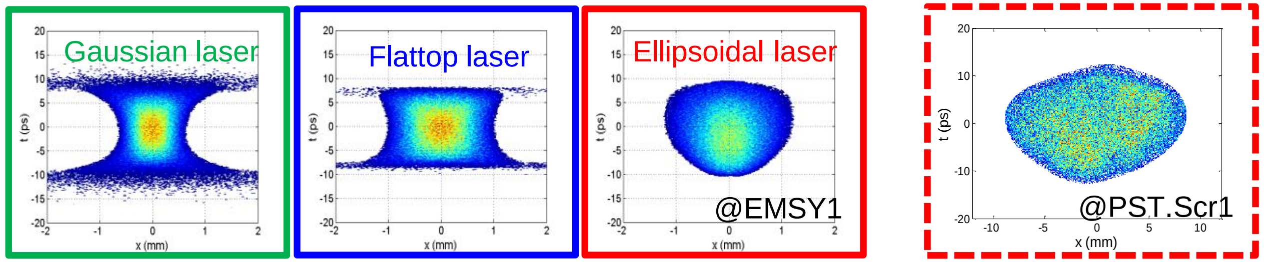
Towards 3D ellipsoidal electron bunches with IAP (Nizhny Novgorod)

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



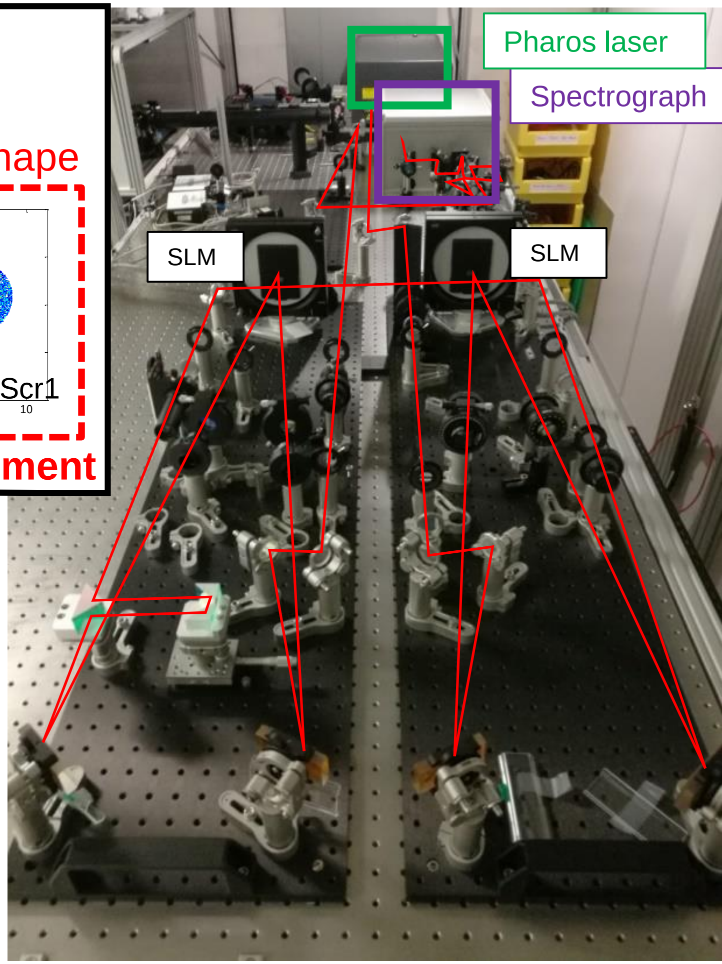
Proof of principle demonstrated with IAP system at PITZ in 2016 (single SLM → dual path)

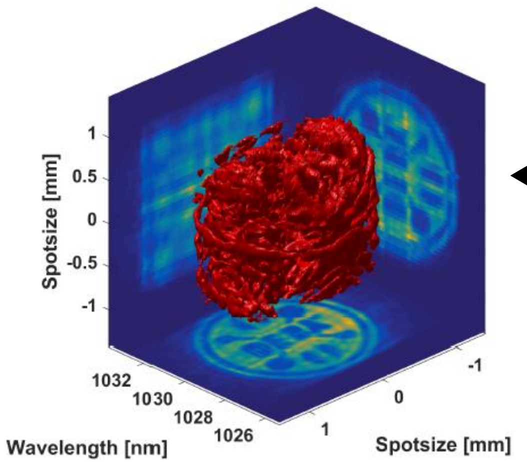
Comparison with simulated e⁻ beam shapes (500pC): similarity in shape



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

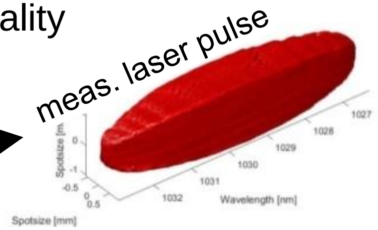
First Measurement





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,** experimental tests expected soon
- Cylindrical symmetry problem to be studied with volume Bragg grating



Work continues !

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

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

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**	100 kHz, 254 kHz, 564 kHz, 1.125 MHz, **2.25 MHz**, **4.5 Mhz** **(other frequencies TBD)**
Wavelength	257 nm	257 nm	257 nm
Pulse energy for long pulse	10 uJ	**5 uJ**	**5 uJ**
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 uJ		**5 uJ**
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

Courtesy of Lutz Winkelmann

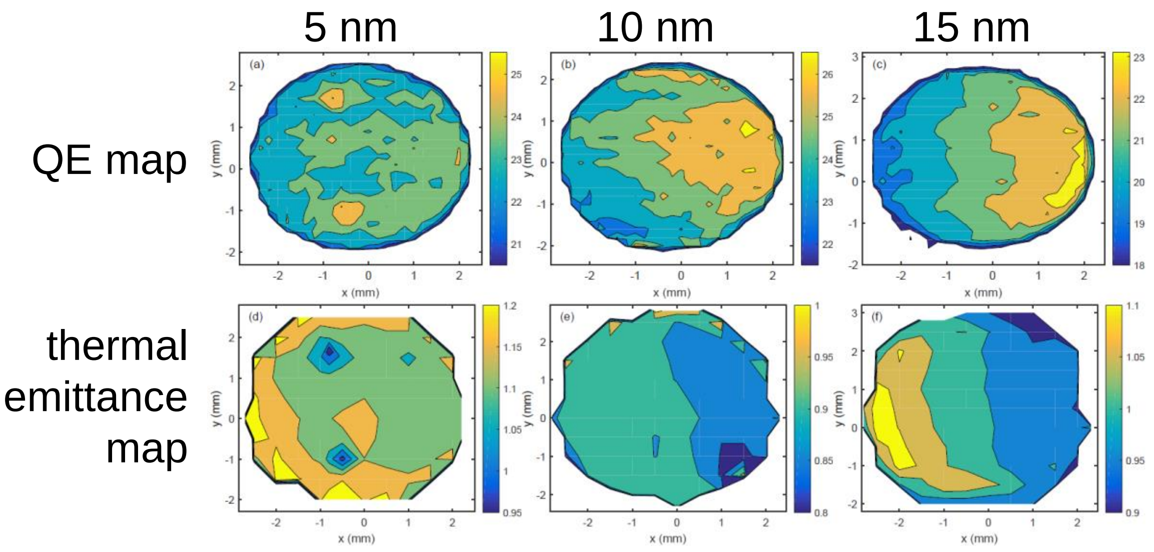
Installation at PITZ expected 1st half of 2023, will replace MBI system

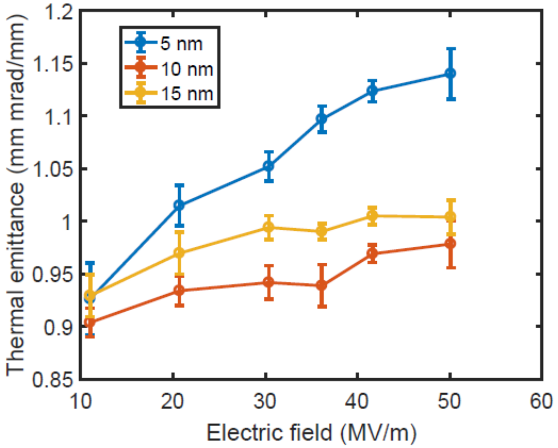
Photo cathode developments

Up to now mainly UV cathodes (Cs2Te) were used at PITZ, INFN LASA Milano develops new green cathodes

Cs2Te:

- Developments for DESY machines for were done by **INFN LASA Milano**
- Standard production for DESY's facilities (XFEL, 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)

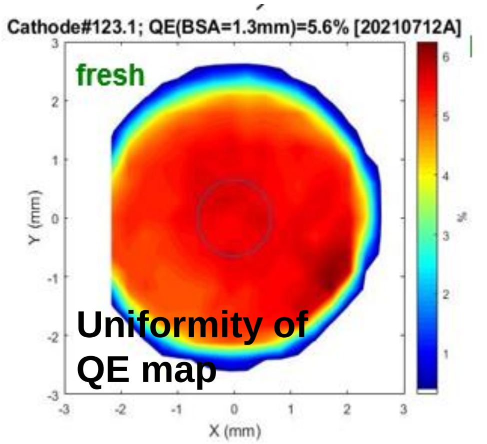
Green cathodes:

- Emission at **green** PC laser **wavelength**
- Aim for
  - **Lower thermal emittance**
  - **Simplified photo cathode laser system** → omitting conversion to UV leads to
    - Lower primary laser energy required
    - **Less degradation of laser pulse shaping**
  - Low **dark current**, high **life time** + **robustness** to be maintained
- New developments at LASA ongoing …

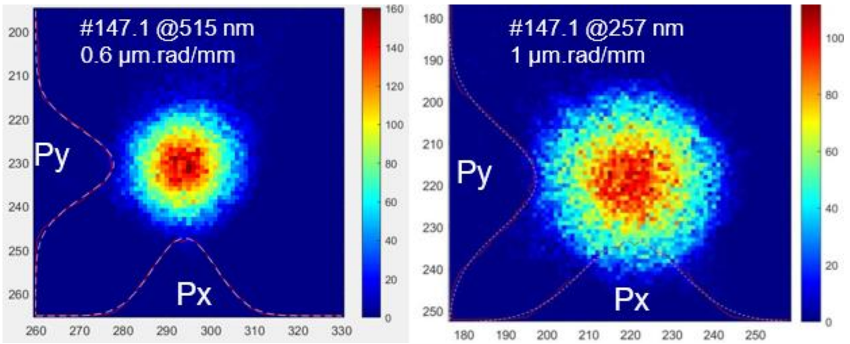
Green photocathodes for high-brightness RF photoinjectors

KCsSb Photocathodes → lower therm. emittance, simplified PC laser

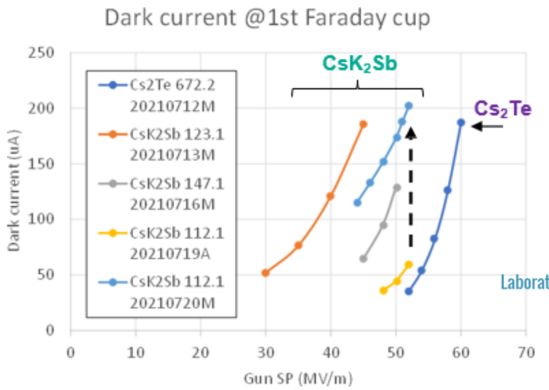
- INFN LASA successfully produced the first batch of 3 green cathodes in “new production system” with sequential deposition and varying thickness (1 thick and 2 thin cathodes).
  - **3-7 %** Q.E @514 nm is recorded after production for thick and thin cathodes
- Test results in PITZ RF gun:
  - **Above 30-40 MV/m**, much more vacuum events than Cs_2Te conditioning → degrades QE significantly
  - **QE drops from 3-6% to below 1% in 2 days**
  - **Thermal emittance**
    - **Green** 2.4eV @19 MV/m, **~0.6 mm.mrad/mm**
    - **UV** 4.8eV @19 MV/m, ~**1** mm.mrad/mm
  - **Response time**
    - One good dataset for #147.1, preliminary analysis shows **below ~100 fs**, much shorter than Cs_2Te (~**200 fs**).
  - Relatively **high dark current** is observed compared to Cs_2Te photocathode.
- **Future plans:**
  - Cathode degradation studies at different setup temperatures, gases etc.
  - **Improve and further optimize the cathode recipe.**
  - Develop a reproducible growth procedure for NaKSb(Cs) photocathode.
  - Surface characterization study



2D distribution of photoemission transverse momentum:



Dark current:



INFN LASA
Istituto Nazionale di Fisica Nucleare
Laboratorio Acceleratori e Superconduttività Applicata

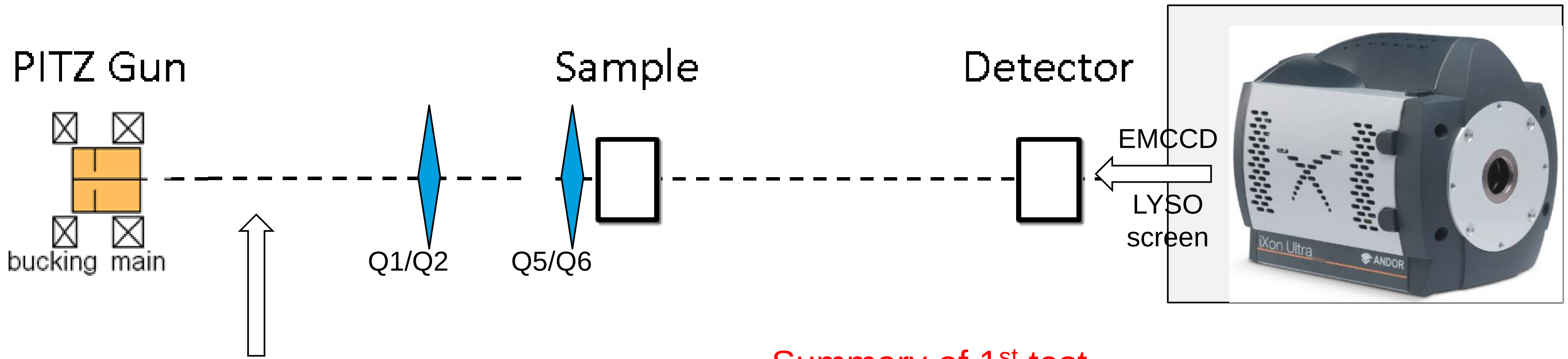
II) Other high brightness beam applications:

- Tests towards UED studies
- R&D on beam driven plasma acceleration
  - a) experimentally proving self-modulation instability
  - b) high transformer ratio measurements
- Generating bunch microstructure via dielectric lined waveguides
- THz SASE FEL
- FLASH radiation therapy and radiation biology

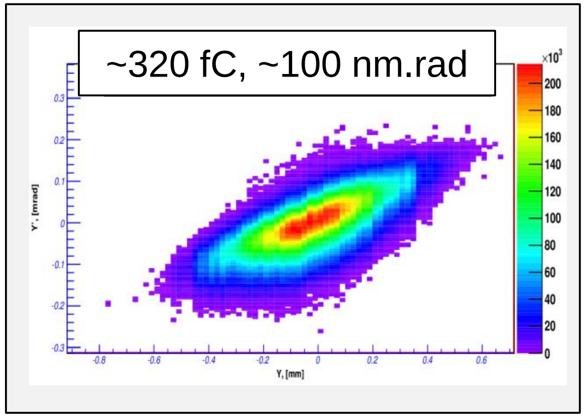
First static electron diffraction tests at PITZ in 2017

Collaboration between PITZ, Max-Born-Institute (MBI) and Fritz-Haber-Institute (FHI)

- PITZ bunch train (up to ~10^4 pulses/sec) reduces signal accumulation time for diffraction patterns for better signal to noise ratio.



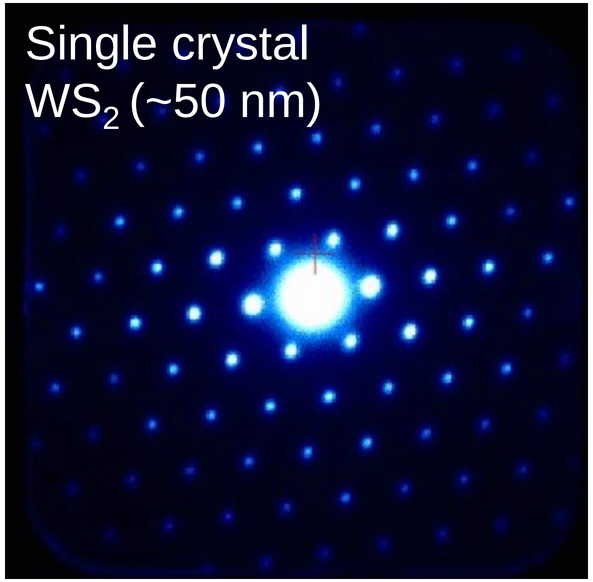
Emittance measurement

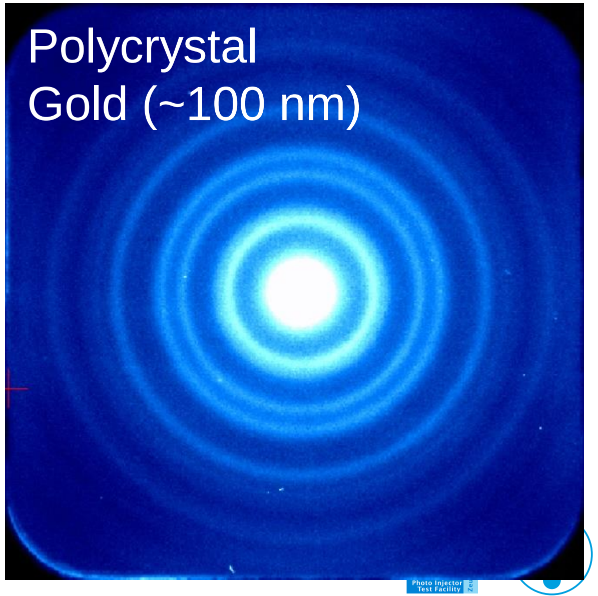


Summary of 1st test

e^- beam at sample	1st Test	Unit
Energy	~4	MeV
Electron per pulse	~2×10^6	e^-/pulse
Bunch FWHM length	~2*	ps
Normalized emittance	~100	nm.rad
RMS beam size at sample	~200	µm
Transverse coherence length	~1.9**	nm

*Buncher off. **No beam aperture yet.





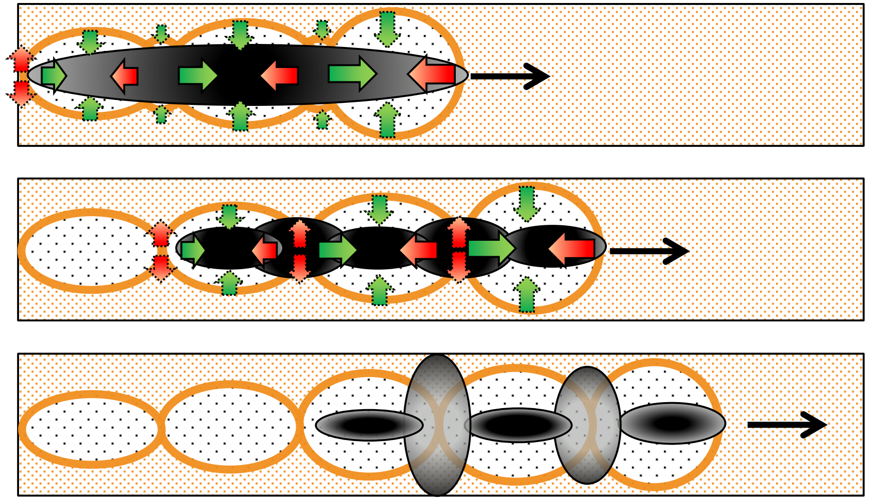
R&D on beam driven plasma acceleration → Part a)

Self-modulation instability (SMI), background & scope of experiments at PITZ

Instability physics

- **Transverse modulation** of long bunches ($L_{bunch} >> \lambda_{plasma}$)
- Initiated by inhomogeneities in focusing forces
- **Providing proton driver** trains for PWFA (**AWAKE@CERN**: Convert proton beam energy to accelerate electron beam **in single stage**)

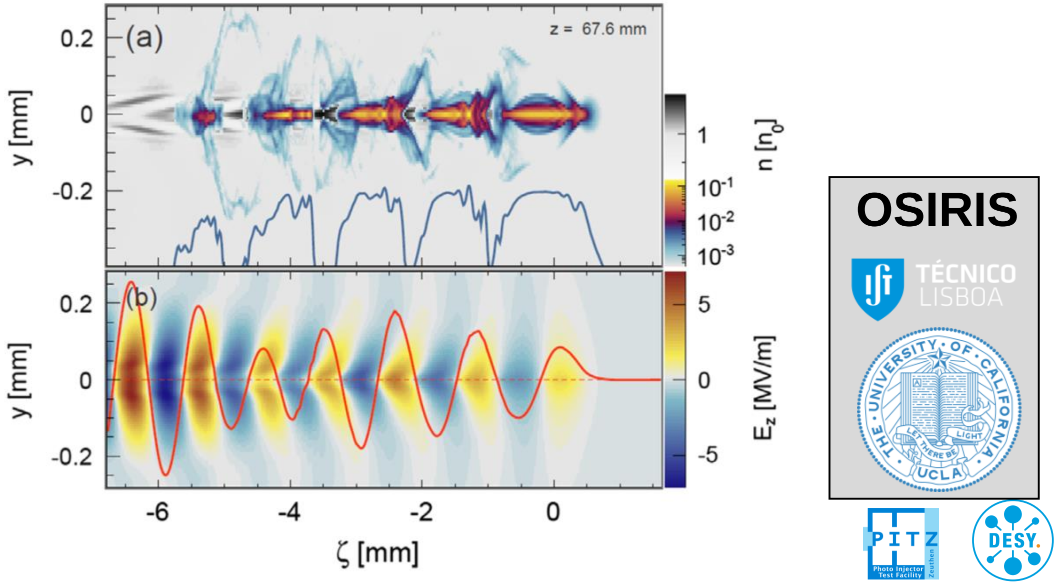
SMI principle:



Self-modulation at PITZ

- **Proof-of-principle** experiments
- Modulate **flat-top electron bunches**
- Investigate dynamics of instability, test theory models

Simulations

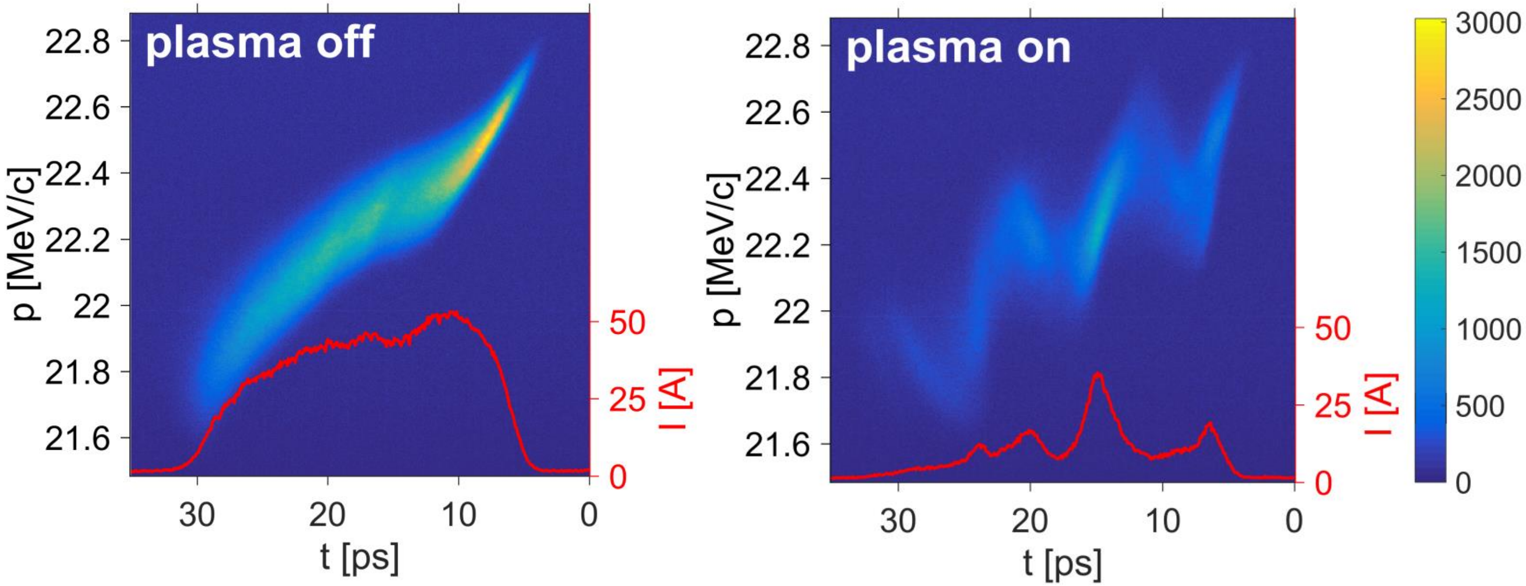


Highlight: Self-Modulation of a Long Electron Bunch

@PITZ: first unambiguous experimental signature was revealed by RF deflector in autumn 2016

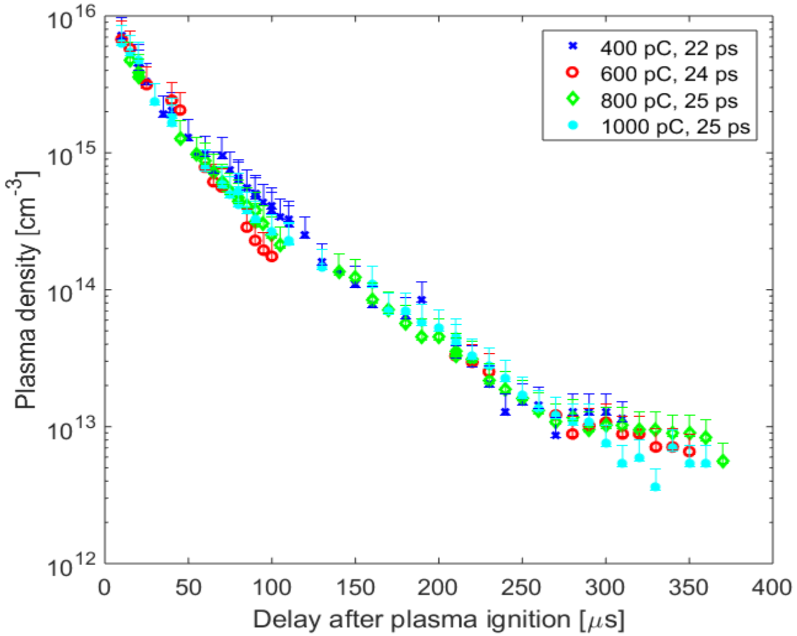
- **Demonstration at PITZ:** characterization of self-modulation with electron beam

Longitudinal phase space (n_p ~$4x10^{14}$ cm^{-3})



M. Gross et al., PRL 120, 144802 (2018)

- Utilizing the Self-Modulation Instability (SMI) as an online diagnostics tool



✓ Results fit well to spectroscopic measurements
✓ Measurements extended to lower densities

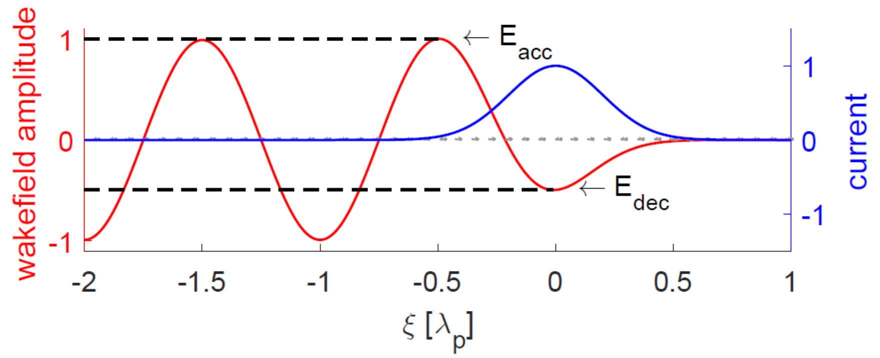
G Loisch et al., PPCF 61 045012 (2019)

R&D on beam driven plasma acceleration → Part b)

High Transformer Ratio (HTR) wakefields increase ratio of acceleration to deceleration

- **Plasma wakefield ~ transformer → Energy-transfer from driver to witness**
- Fundamental theorem of beamloading: **TR = E_{acc}/E_{dec} <2** (symmetrical driver, linear theory)
- High TR **enables high energy gain or high efficiency**
- **Asymmetrical bunch shapes** proposed

  → TR ≤ 2π $L_{driver}/\lambda_{plasma}$

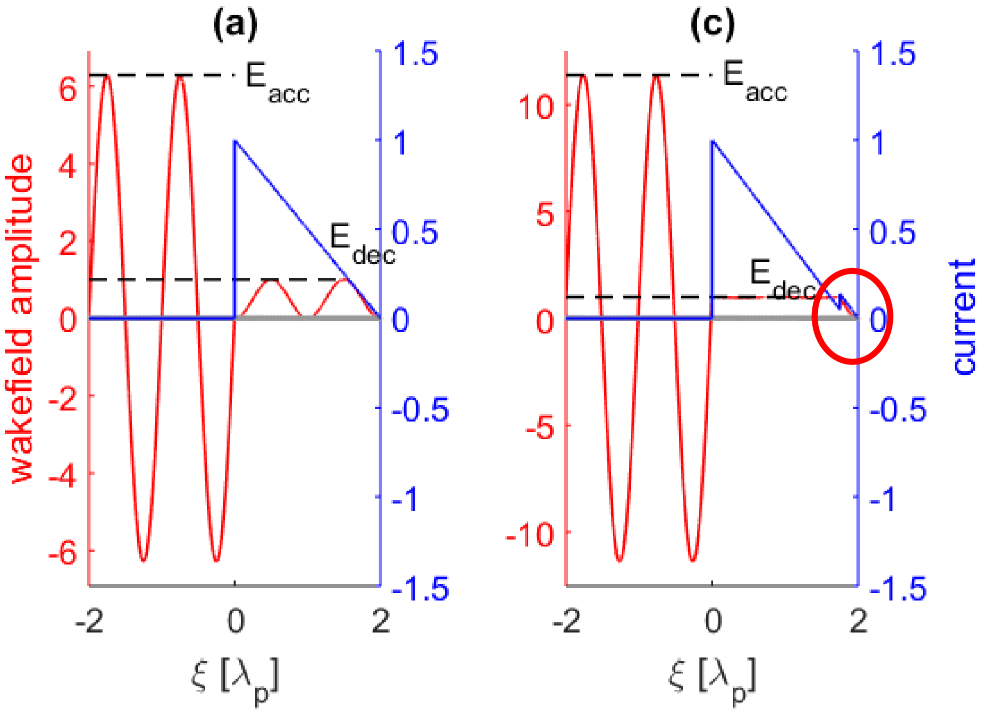


HTR in PWFA

➢ λ_{plasma} ≤ mm → **ps-scale bunch shaping**

➢ Driver length = several periods of wake → instability

  → operation in **(quasi-) nonlinear regime: n_{bunch} > n_{plasma}**

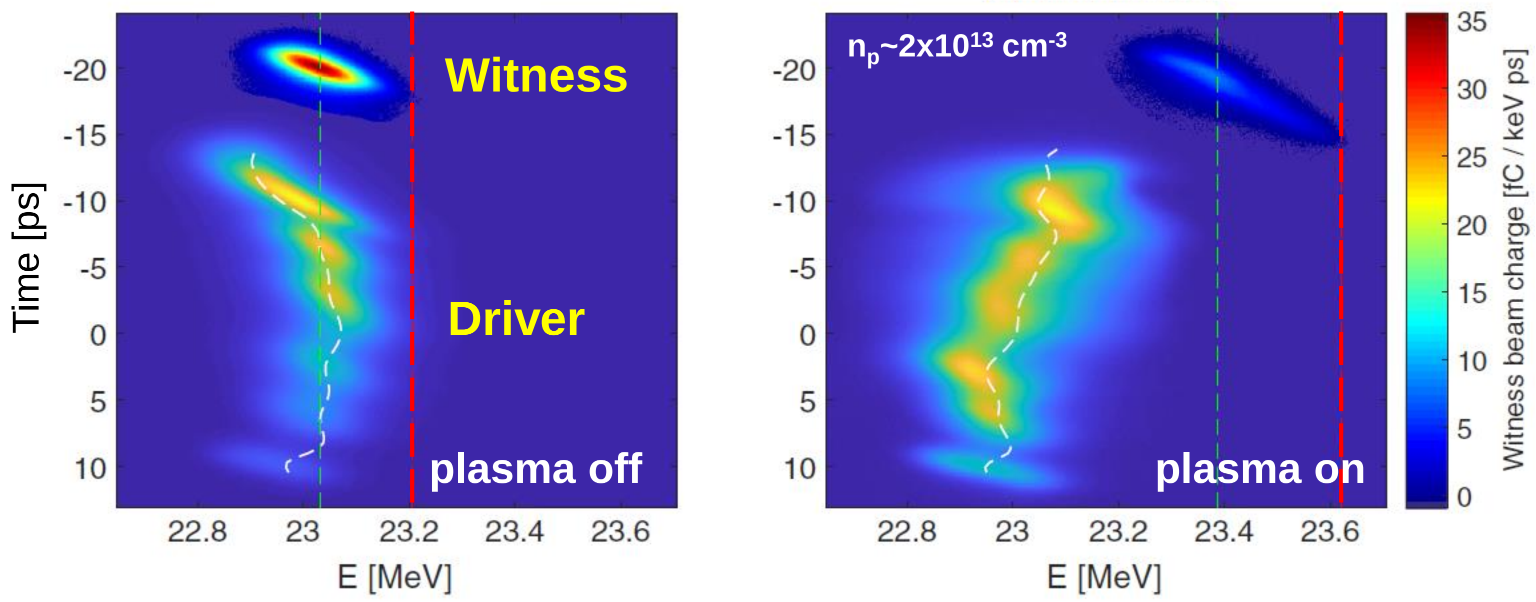


Highlights: High Transformer Ratio in Plasma

First detection of increased transformer ratio with shaped driver in plasma

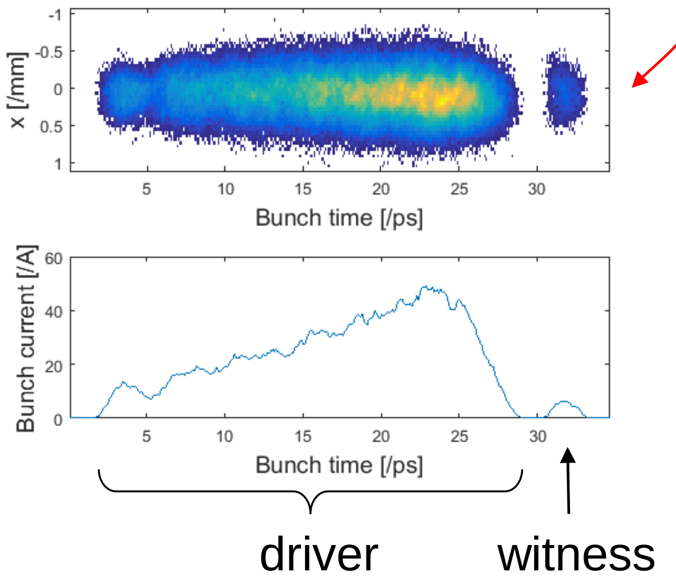
- **Demonstration at PITZ:** Time resolved energy measurement (slice energy) by using ~double triangular drive bunch

- **Experimental result:** $\mathbf{TR = 4.6^{+2.2}_{-0.7}}$



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

Measured electron bunch profile

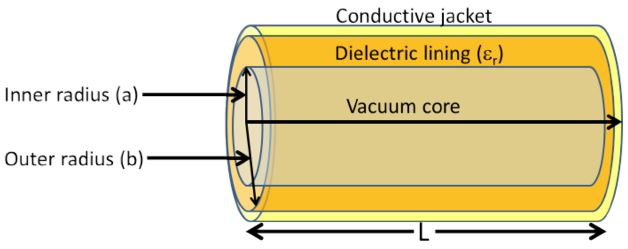


→ **G. Loisch *et al*., "Photocathode laser based bunch shaping for high transformer ratio plasma wakefield acceleration", NIM A, *909, pp. 107-110 (2018)***

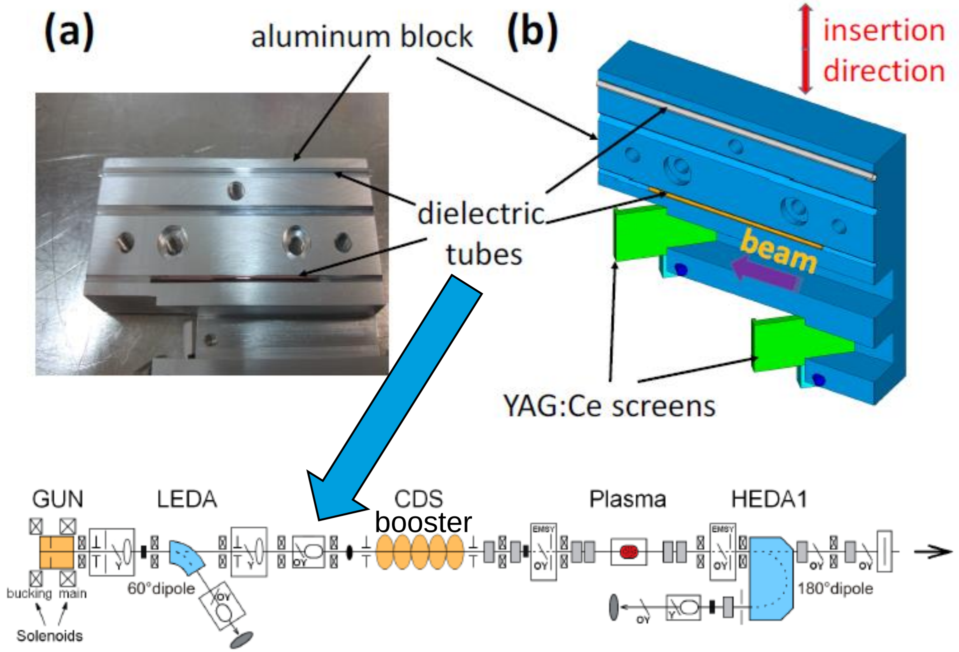
Bunch Microstructure Generation with DLWs at PITZ

PIs: F. Lemery (CFEL, DESY) and P. Piot (APC FNAL) *et al.*, *Phys. Rev. Lett.* **122**, 044801 (2019)

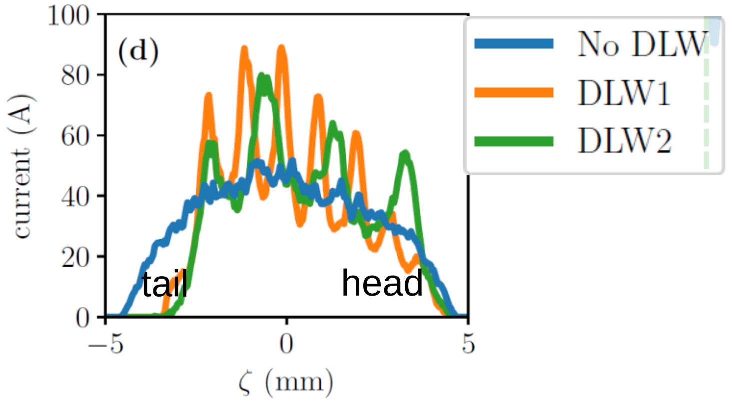
Using Dielectric Lined Waveguides - DLW



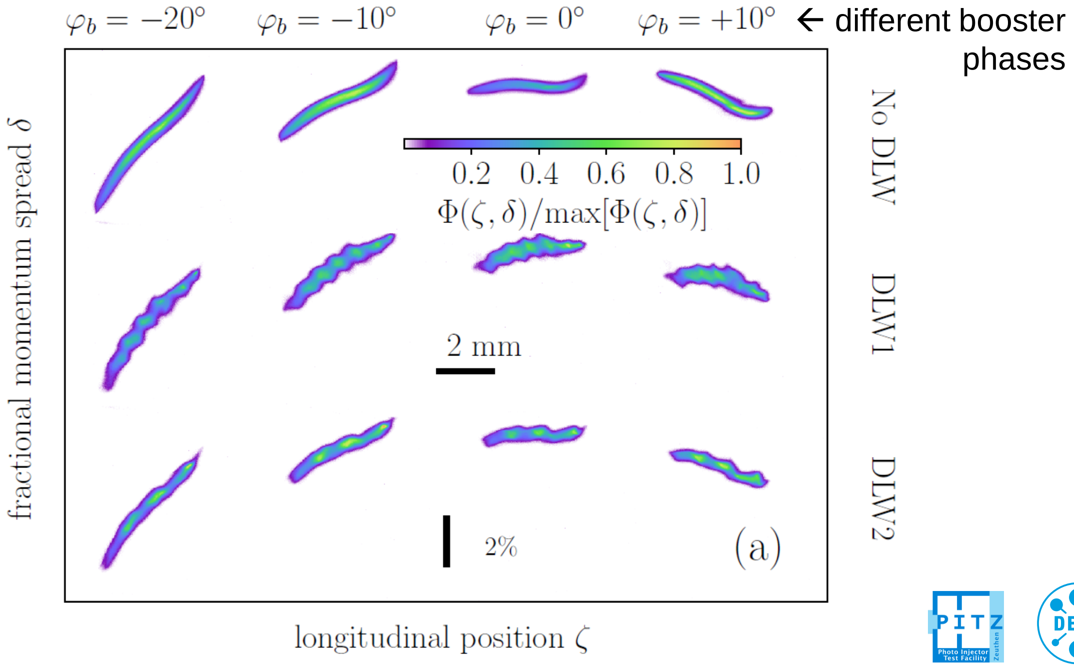
parameter	symbol	nominal	range	unit
laser launch phase	ϕ_l	0	–	deg
laser spot radius	r_l	2	–	mm
laser pulse duration	L_t	13	[10, 20]	ps
RF gun peak field	E_0	60	[45, 60]	MV/m
linac phase	φ_b	0	[-20, +10]	deg
linac voltage	V_b	14	[10, 18]	MV
bunch charge	Q	1.1	[0.020, 2]	nC
beam momentum	$\langle p \rangle$	21.8	[16, 22]	MeV/c
DLW permittivity	ε_r	4.41	–	–
DLW1 inner radius	a_1	450 ± 50	–	μm
DLW1 outer radius	b_1	550 ± 50	–	μm
DLW1 length	l_1	50.0 ± 0.1	–	mm
DLW2 inner radius	a_2	750 ± 50	–	μm
DLW2 outer radius	b_2	900 ± 50	–	μm
DLW2 length	l_2	80.0 ± 0.1	–	mm



E-beam current profiles

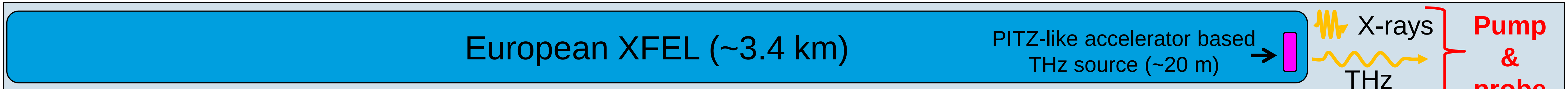


Measured Longitudinal Phase Spaces



THz SASE FEL Developments at PITZ

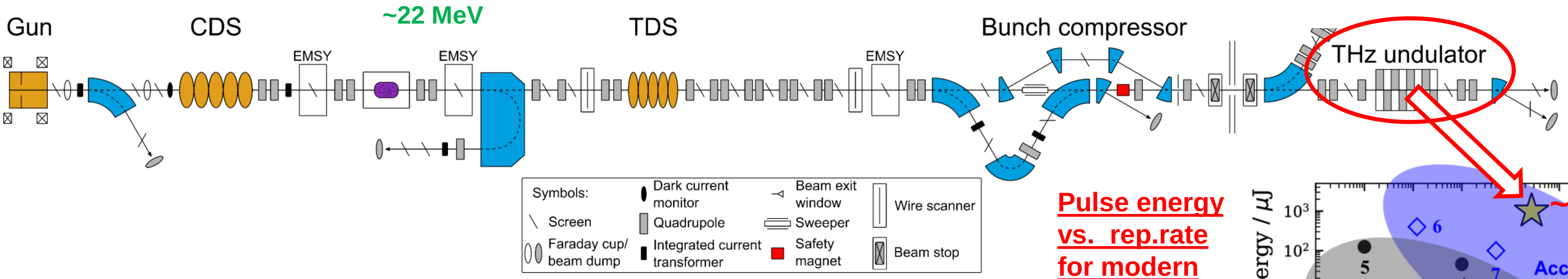
Accelerator-based, high power (peak + av.) THz source for pump-probe experiments at European XFEL



*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***

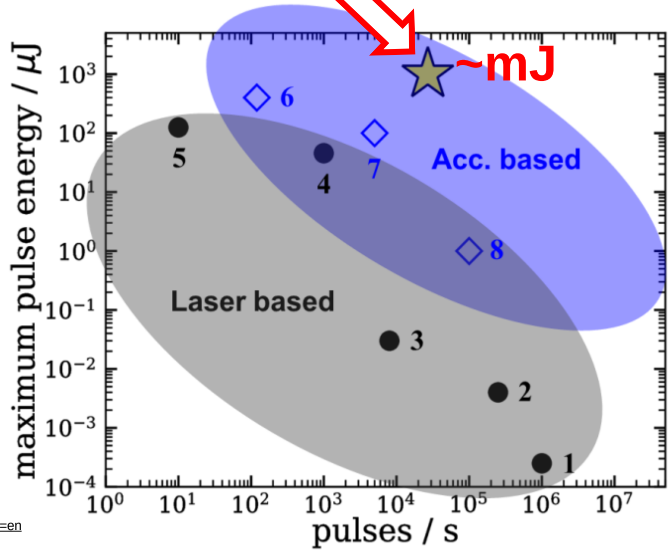
➔ PITZ-like accelerator allows mJ level THz at E-XFEL repetition rate

PITZ schematics:



➔ A proof-of-principle experiment is co-funded by the E-XFEL Management Board since 2019.

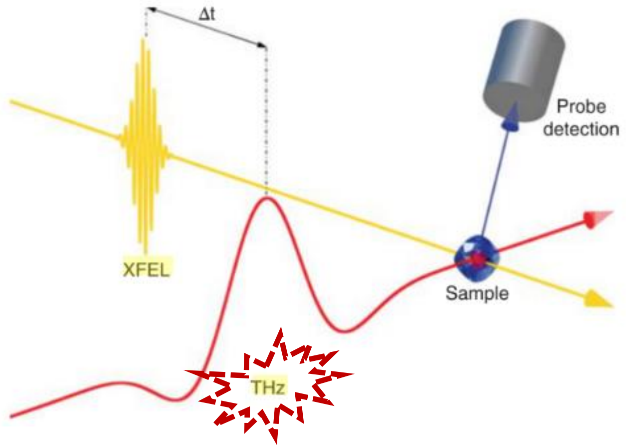
Pulse energy vs. rep.rate for modern THz sources:



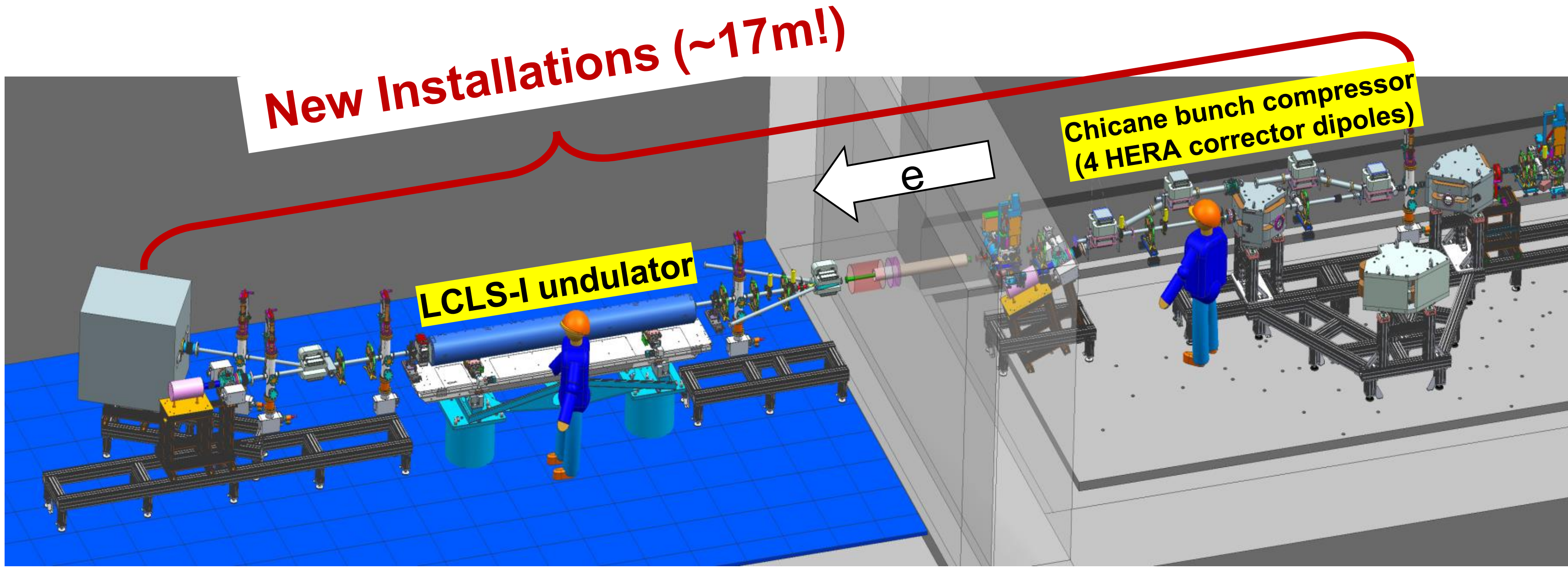
1,3-5: Optical rectification[1]
2: photoconductive antenna [1]
6: CTR (LCLS/FACET) [2]
7: UR (FLASH) [3]
8: UR (TELBE) [4]

[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

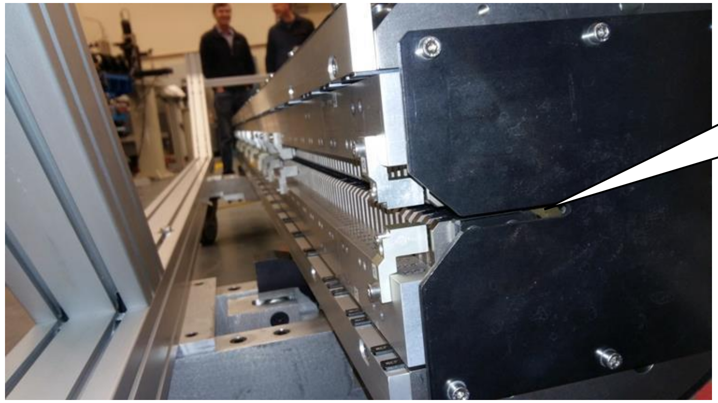
THz@PITZ: Application and extended PITZ beamline



An Introduction to Synchrotron Radiation: Techniques and Applications, Philip Willmott,, John Wiley & Sons,2011, ISBN 0470745789, 9780470745786



LCLS-I undulator from SLAC



Vacuum chamber:
5 x 11 mm
3.4 m long

⇩

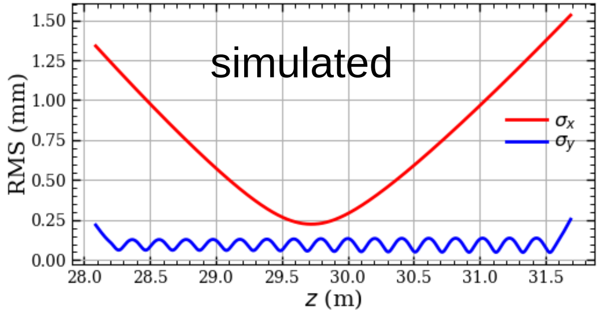
challenge to transport
≤4 nC with 17 MeV

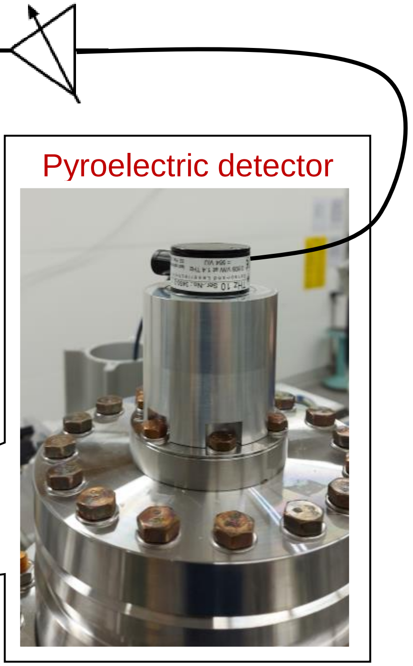
Applications:

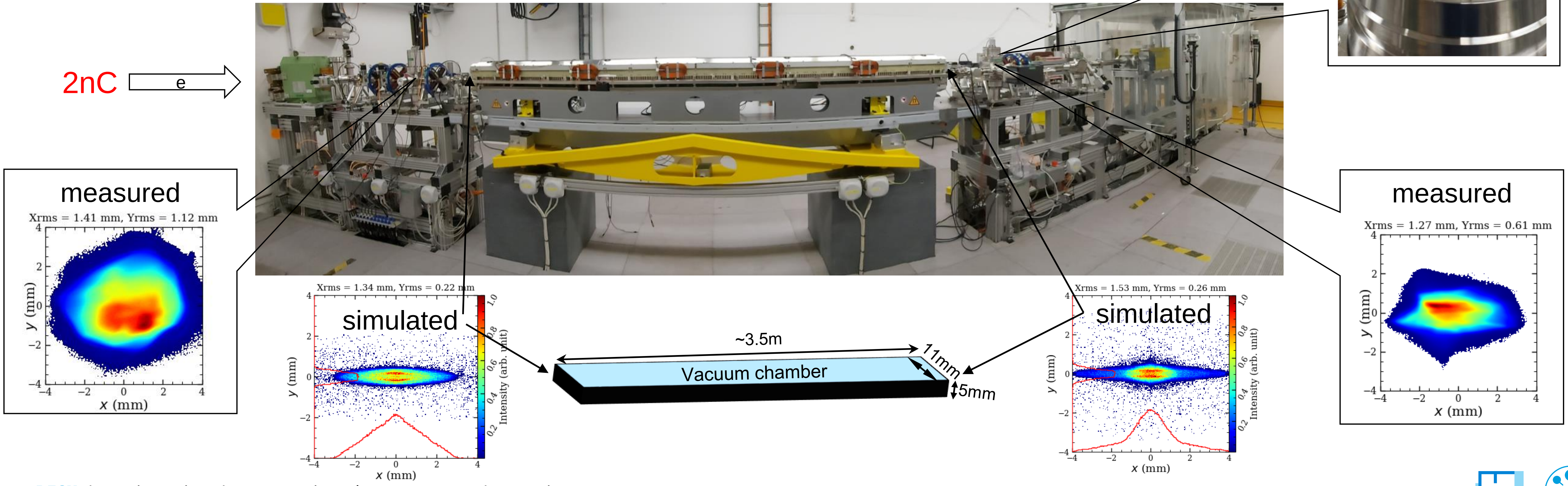
- Studies of protein dynamical transitions and tertiary native proteins with structural motions
- Characterization of ions and molecules where solvation process plays a relevant role in the modification of their structure and properties.
- Condensed matter physics: the study of non-linear effects aiming to the control the state of material which could lead to new applications.
- Phase change of materials.
- Highly correlated materials (magnetoresistance, ferroelectrocity, superconductivity, insulator-to-metal transitions, etc).

THz SASE FEL at PITZ

Electron beam matching for lasing







THz SASE FEL at PITZ: First Characterization

FEL2022

FEL Gain Curves


FIRST LASING OF THE THZ SASE FEL AT PITZ*

M. Krasilnikov †, Z. Aboulbanine, G. Adhikari, N. Aftab, P. Boonpornprasert, R. General, G. Georgiev, J. Good, M. Gross, L. Heuchling, A. Hoffmann, M. Homann, L. Jachmann, D. Kalantaryan, W. Köhler, G. Koss, X.-K. Li, A. Lueangaramwong, S. Maschmann, D. Melkumyan, F. Müller, R. Netzel, R. Niemczyk, A. Oppelt, B. Petrosyan, S. Philipp, M. Pohl, H. Qian, A. Sandmann-Lemm, M. Schade, E. Schmal, J. Schultze, F. Stephan, G. Vashchenko, T. Weilbach, DESY, Zeuthen, Germany

B. Krause, E. Schneidmiller, M. Tischer, P. Vagin, M. Yurkov, DESY, Hamburg, Germany

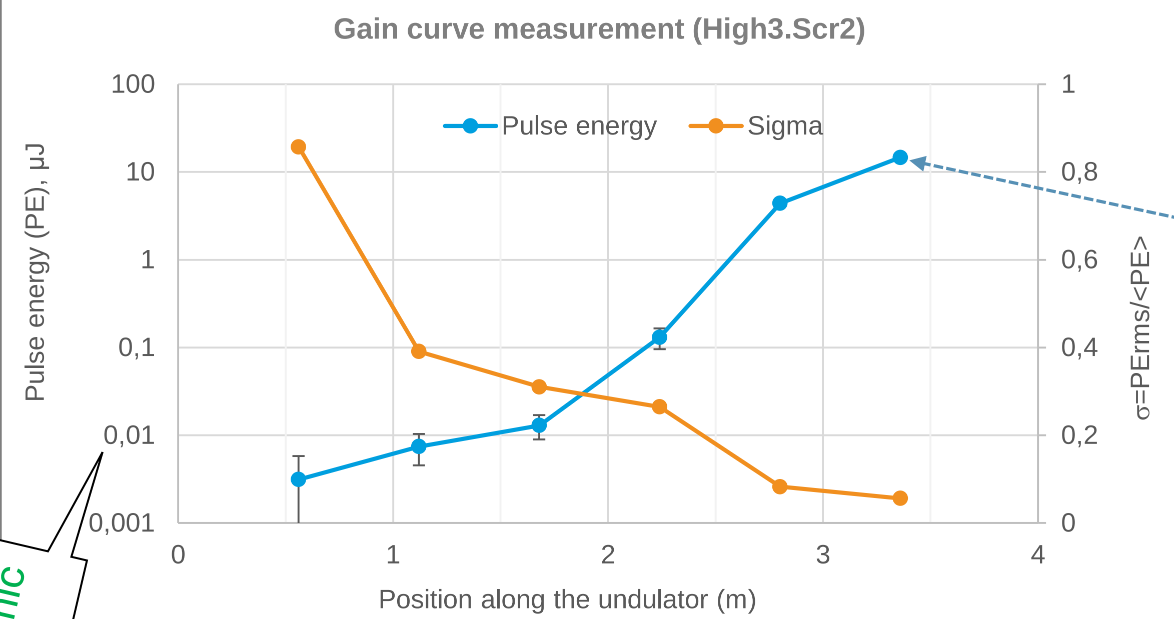
A. Brachmann, N. Holtkamp, H.-D. Nuhn, SLAC, Menlo Park, USA

Abstract

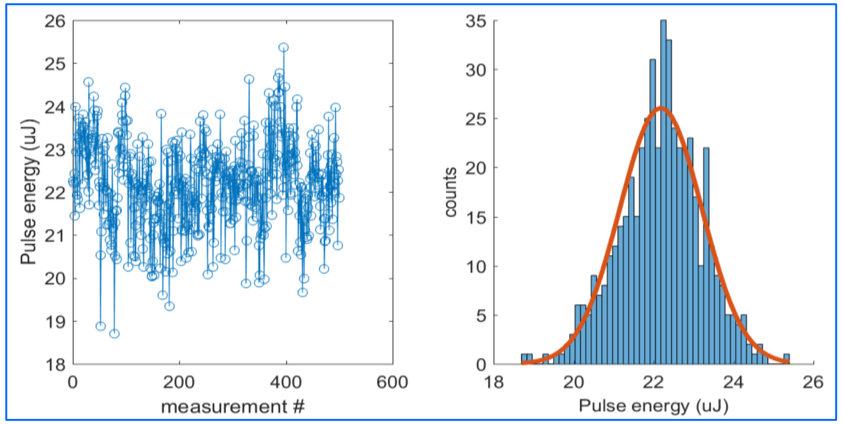
brightness electron source for the European XFEL, properties of the photo injector are fully compatible with the

Operation / THz generation:

- **First lasing at ~100µm ➔ high gain THz SASE FEL at PITZ!**
- Gain curves at 1, 2 and 3nC
- Currently >20µJ (further optimization ongoing)



Recently: Saturation observed for 2nC: <PE>~22µJ



Update 10.10.2022:

~50µJ w/o BPF,

>15µJ with BPF@3THz

Next steps:

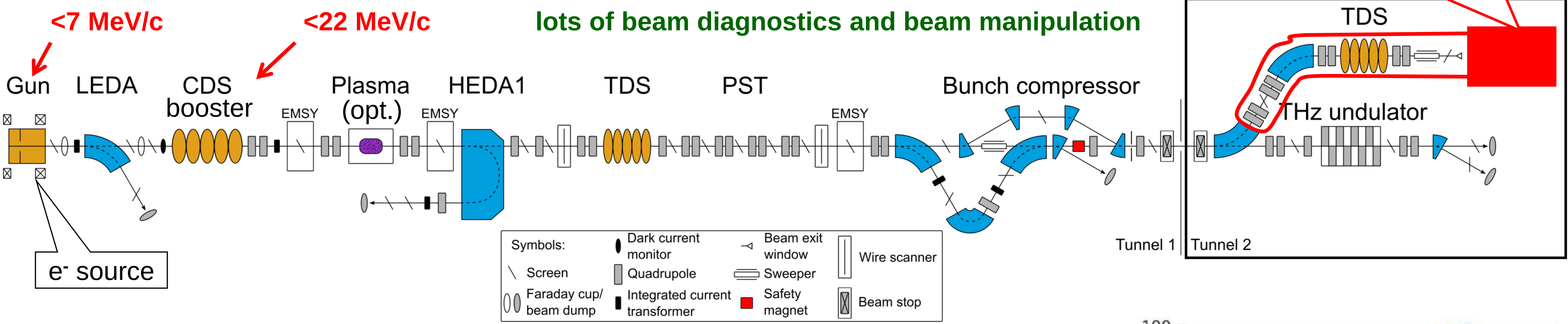
- Detailed tuning of high-charge beam transport/matching
- Setup full THz and e-beam diagnostics
- Other dedicated studies (BC, seeded THz FEL)

New activity: → FLASH*lab*@PITZ

R&D on electron FLASH radiation therapy against cancer

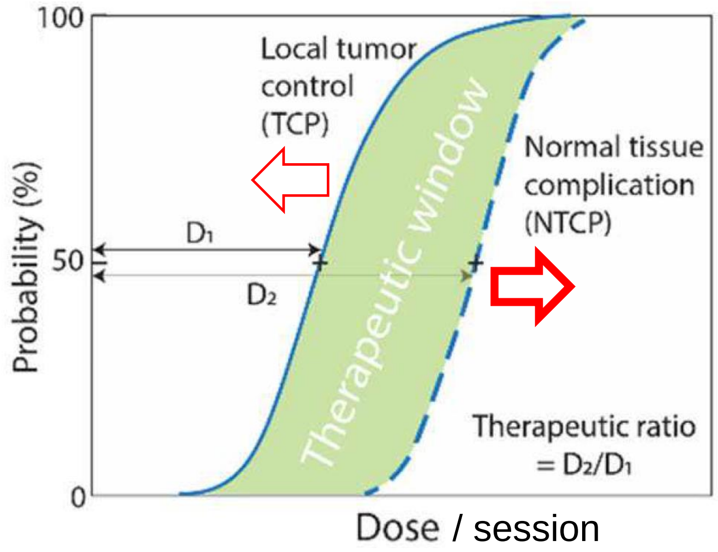
Use existing accelerator
+ external resources

free space for FLASH*lab*@PITZ area:
> 6 x 2 x 3 m³ (l x w x h)



FLASH effect is an 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
    → increasing therapeutic window, reduce treatment time, treating radiation resistant cancer, confine dose to moving cancer

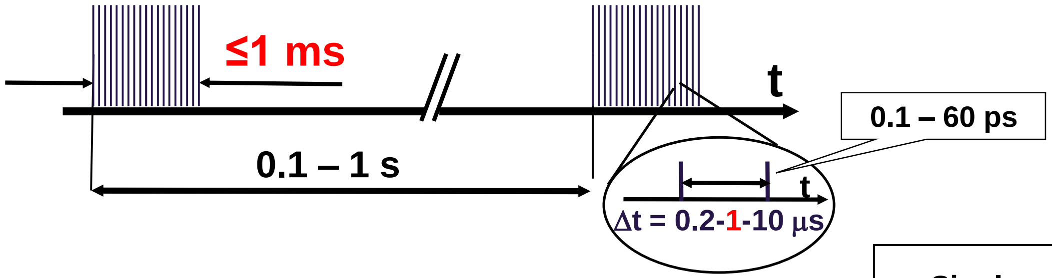


from M.R. Ashraf et al., Frontiers in Physics, 2020, doi: 10.3389/fphy.2020.00328

Unique beam properties at PITZ

allow extremely flexible treatment parameters and dose distribution (in space + time)

- Possibility of **bunch trains** with **up to 1 ms** length:
  - Bunch repetition rate within train 0.1 – 1 MHz (opt. 4.5 MHz)
  - Trains can be repeated with up to 10 Hz
  - ➔ **1 – 1000 bunches in 1 ms (opt. up to 4500)**
  - ➔ 1 – 10 000 bunches in 1 s (opt. up to 45 000)
  - Depending on **bunch charge (<fC – 5nC)** indiv. bunches have
    a) **length** of **~0.1 – 60 ps** (bunch compressor)
    b) **spot size** down to **~100µm**



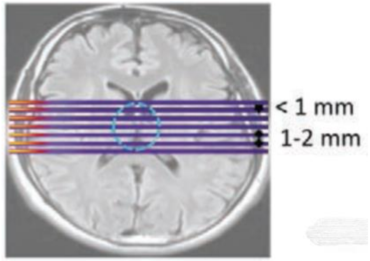
Single bunch: ~9 Gy (cm³)

Two examples:

Options @PITZ:	low dose case	high dose case
Bunch charge [pC]	0.1	5 000
Single bunch OR train	single bunch	1ms train (1MHz)
RF pulse rep. rate	1Hz	10Hz
Bunch length [ps]	<1	~30
Dose │ Dose rate **per bunch** [Gy │ Gy/s]	0.02 │ >2E+10	1000 │ 4E+13
Dose │ Dose rate **per train(ms)** [Gy │ Gy/s]	0.02 │ 20	1E+6 │ 1E+9
Dose **per second** [Gy/s]	0.02	1E+7

Assumptions for table:
~20 MeV e-beam in water with **1mm³** irradiation volume.

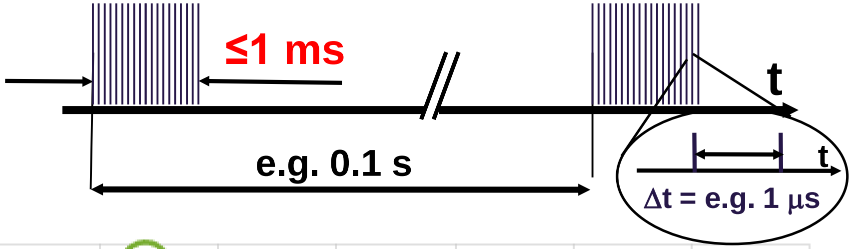
- **Kicker** can be used to distribute the bunches of the bunch train (1ms) over treatment area
  - ➔ **"painting" tumor** with micro beams **within 1 ms**
  - ➔ **~no organ motion**
  - Kicker system is already existing
  - ➔ **possibility of micro beam radiation therapy (MBRT)**

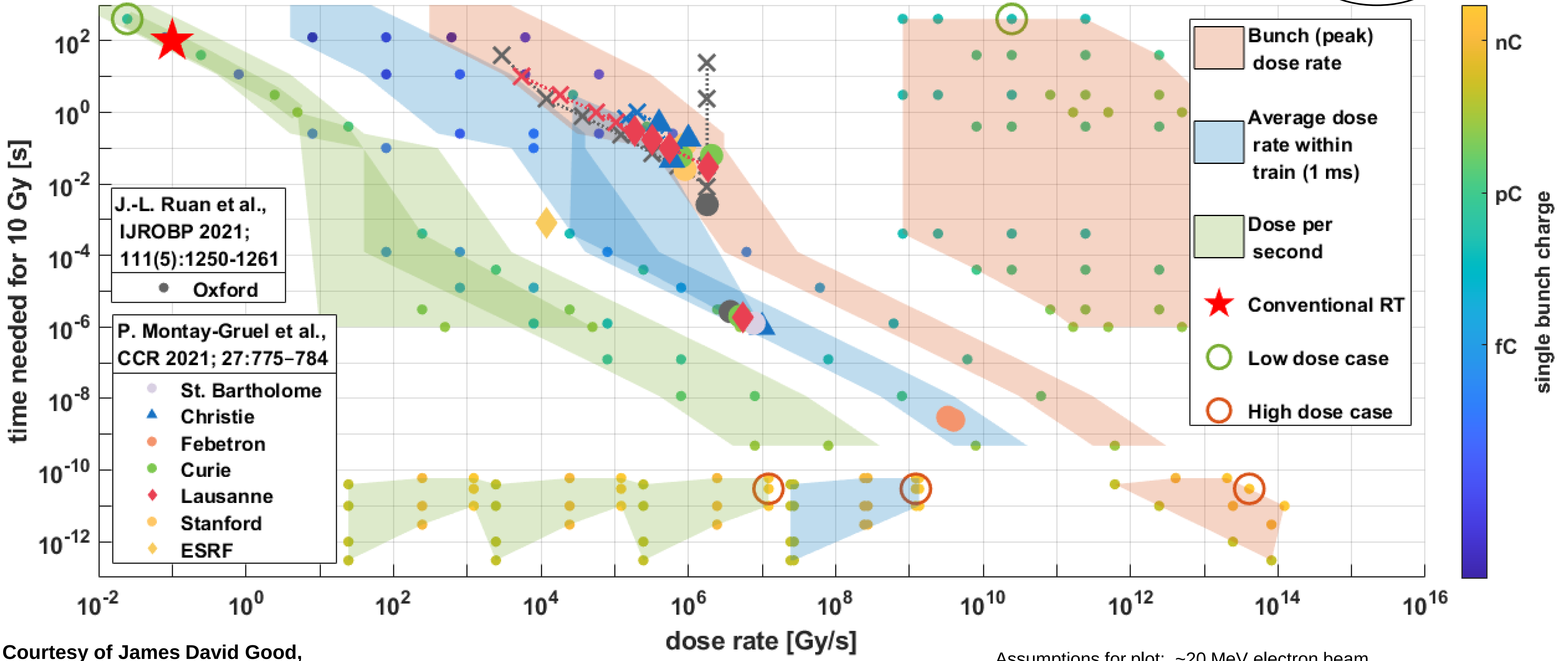


Courtesy of Angeles Faus-Golfe

Parameter space available at PITZ

In comparison with the state-of-the-art up to now





Courtesy of James David Good,
Marie-Catherine Vozenin, Jean-Francois Germond

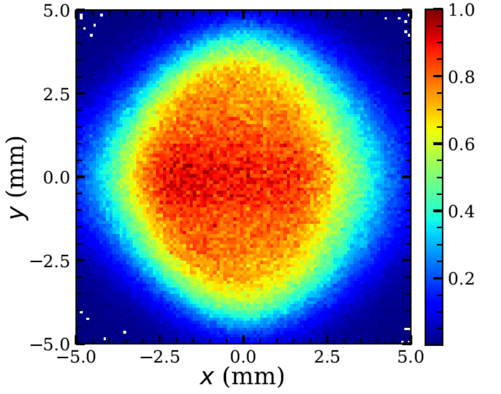
Assumptions for plot: ~20 MeV electron beam in water with **1mm³** irradiation volume.

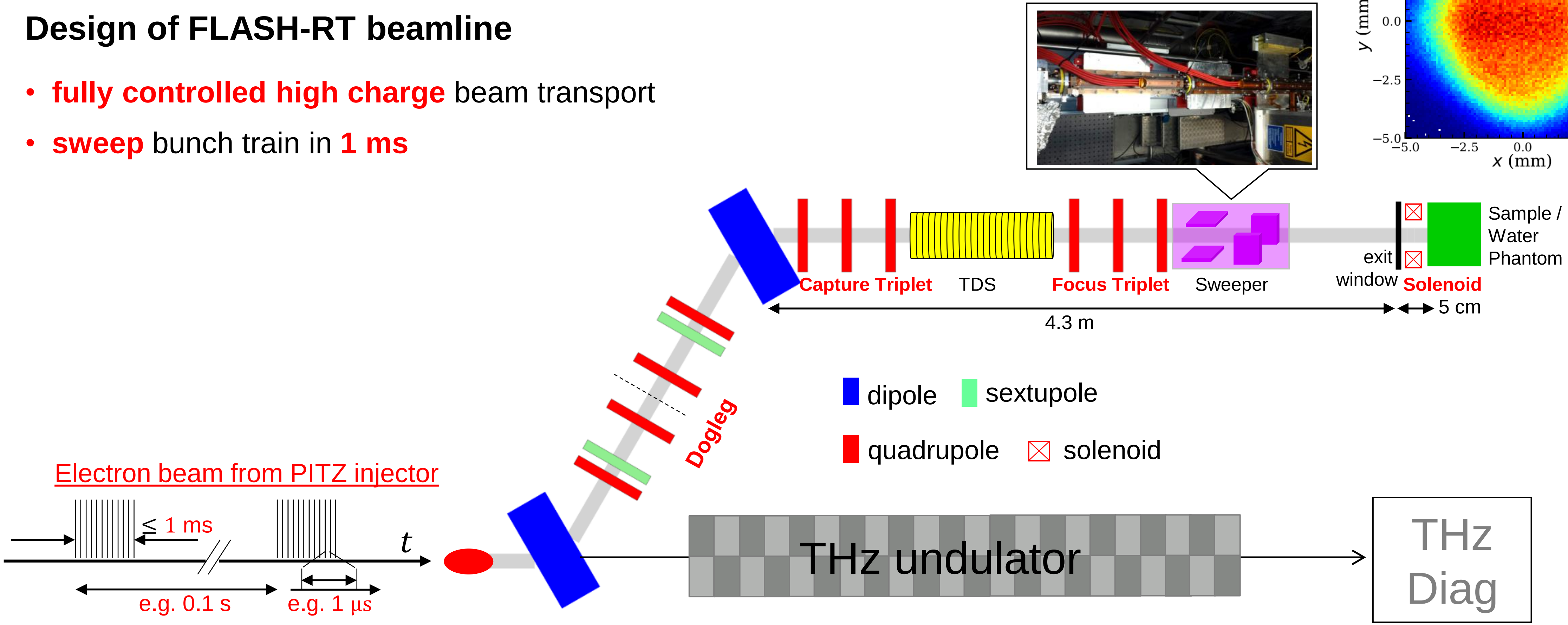
Preparations for FLASHlab@PITZ are ongoing

Beamline design will allow very flexible treatment parameters

- **Design of FLASH-RT beamline**
  - **fully controlled high charge** beam transport
  - **sweep** bunch train in **1 ms**

1 nC, 2 cm after window





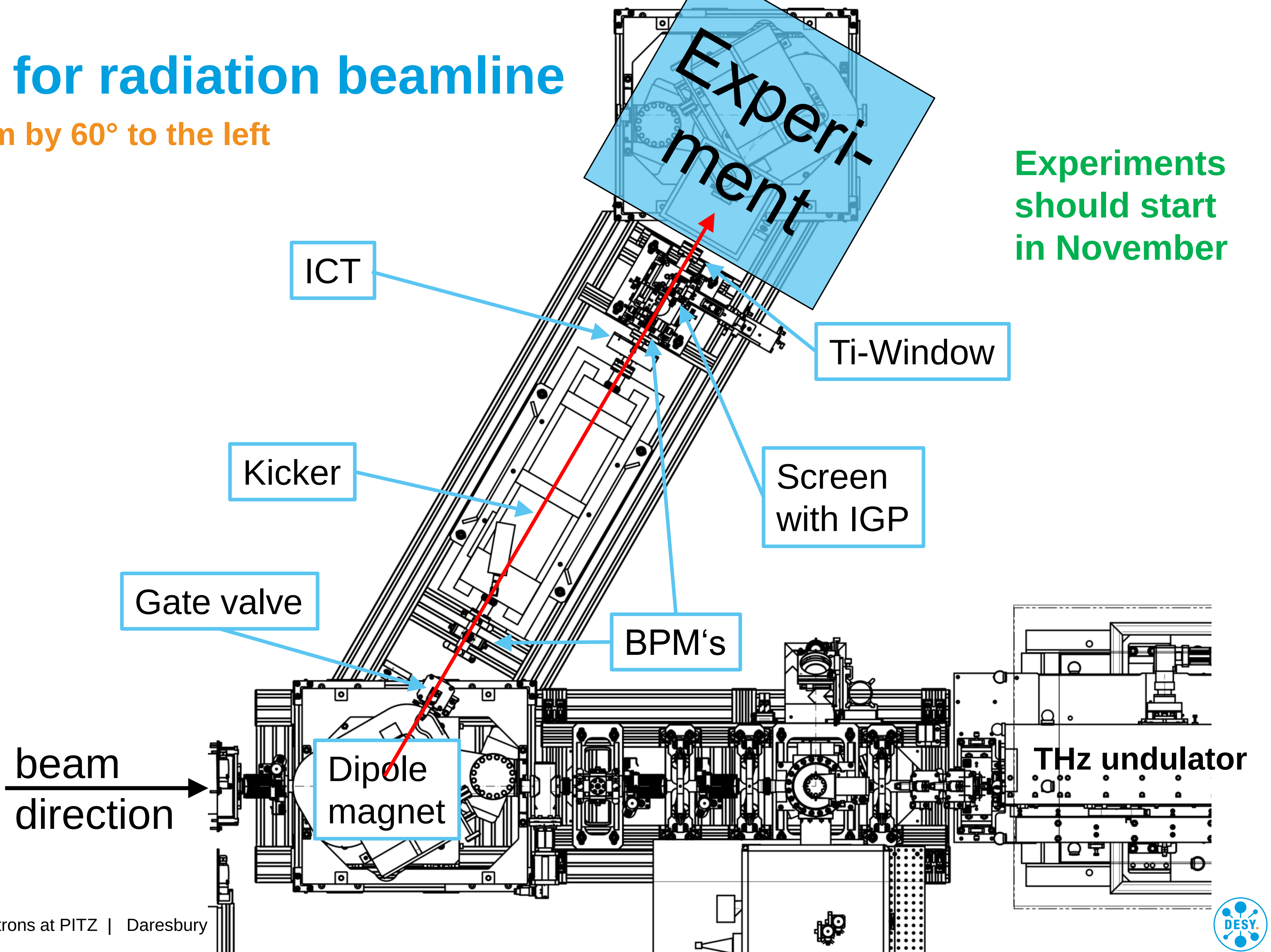
Courtesy: Xiangkun Li, Gregor Loisch, Michael Schmitz

Starting setup for radiation beamline

Dipole deflects the beam by 60° to the left

Order of components

- Gate valve
- Bellows
- BPM
- Bellows
- Kicker
- Bellows
- ICT
- BPM-Screen
- Ti-Window
- Experiment



Experiments should start in November

The project FLASHlab@PITZ schematically:

Cooperation with DKFZ and HZDR in preparation. **Further groups interested are very WELCOME !!!**

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LBNL, UCSF, LLU

FLASH RT

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rad. biology

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Thank you very much to everybody …

… who was/is participating in the success of PITZ:

- to the 25 national and international partners
  [AANL(YERPHI) + CANDLE Yerevan, Charité Berlin, CHUV Lausanne, 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]
- to the many colleagues from different groups at DESY, Hamburg site
- to the many colleagues at DESY, Zeuthen site,
  only some of them shown here →

Thank you for your attention !

Intrest in collaboration:

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