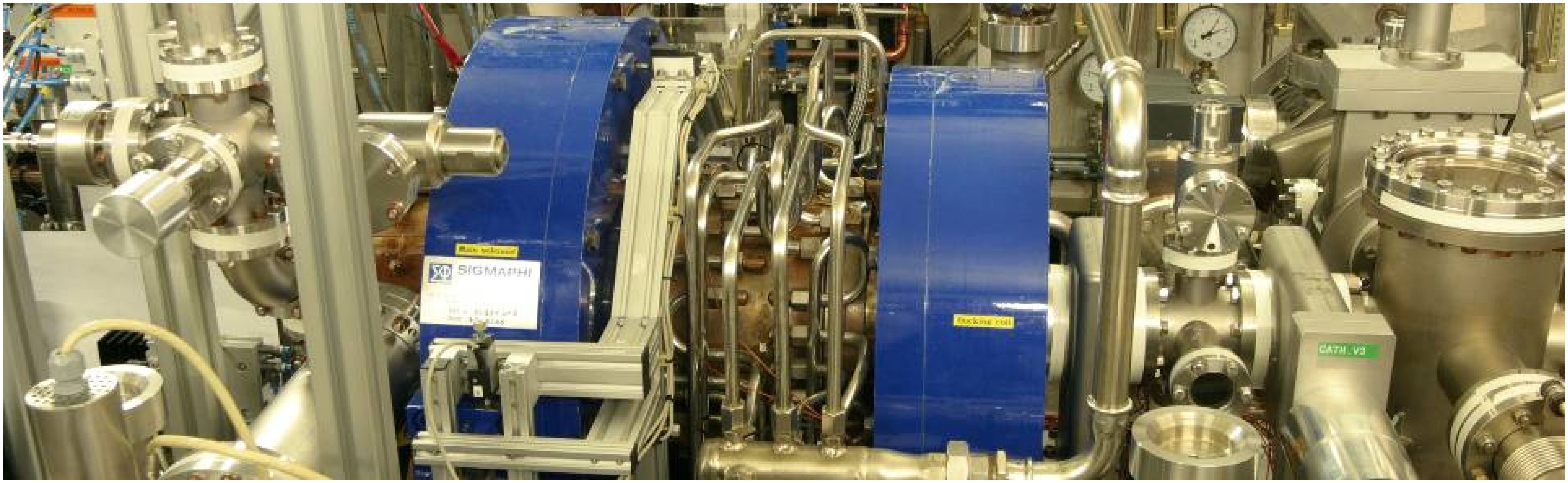
Results from PITZ

Developing the electron source for the European XFEL



Anne Oppelt

Seminar "Physics and Technology of Particle Accelerators"
TEMF, TU Darmstadt
November 12, 2012

Outline

> The European XFEL project

- History and motivation: from TESLA to XFEL
- XFEL: work principle and applications
- Motivation for injector R&D

> Development and characterization of electron sources at PITZ

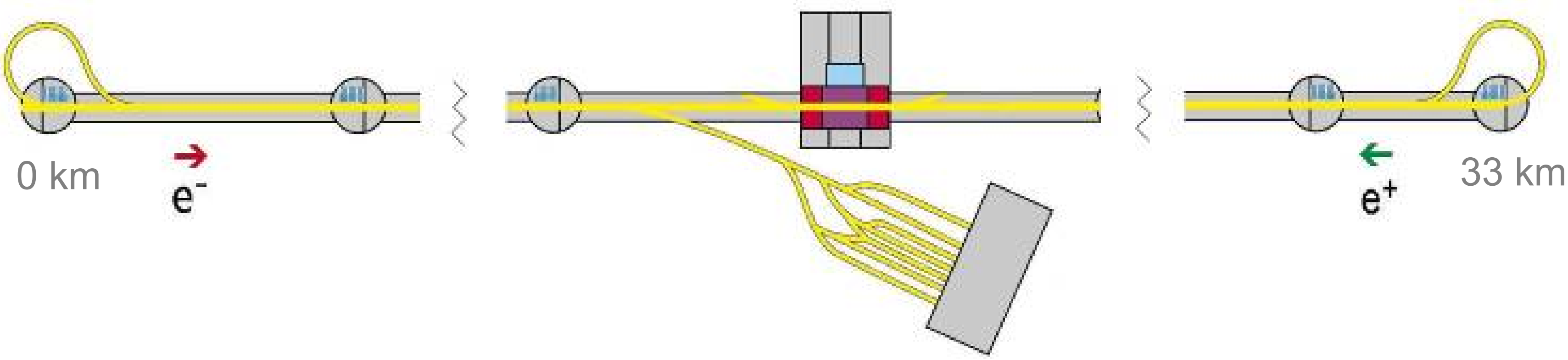
- History of PITZ
- Machine improvements over the last 10 years
- Measurement and optimization of beam parameters
- Achievements in electron beam quality

> Problems and Perspectives

- Comparison of experimental results to simulation
- Possible explanations to solve discrepancies
- Summary

The TESLA project

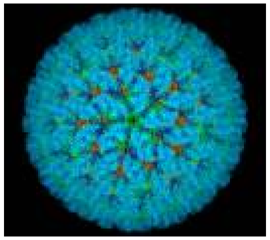
- TESLA = TeV Electron Superconducting Linear Accelerator
- Combination of a new particle physics accelerator for high energy precision measurements with a next generation light source for applied research



Applied Sciences:

- biomolecular systems with atomic resolution
- individual macromolecules
- matter under extreme conditions
- ultra fast dynamics (movies)
- …

→ now *European XFEL*

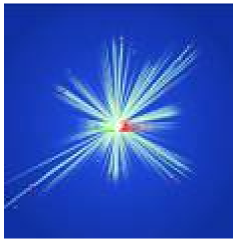


Particle Physics:

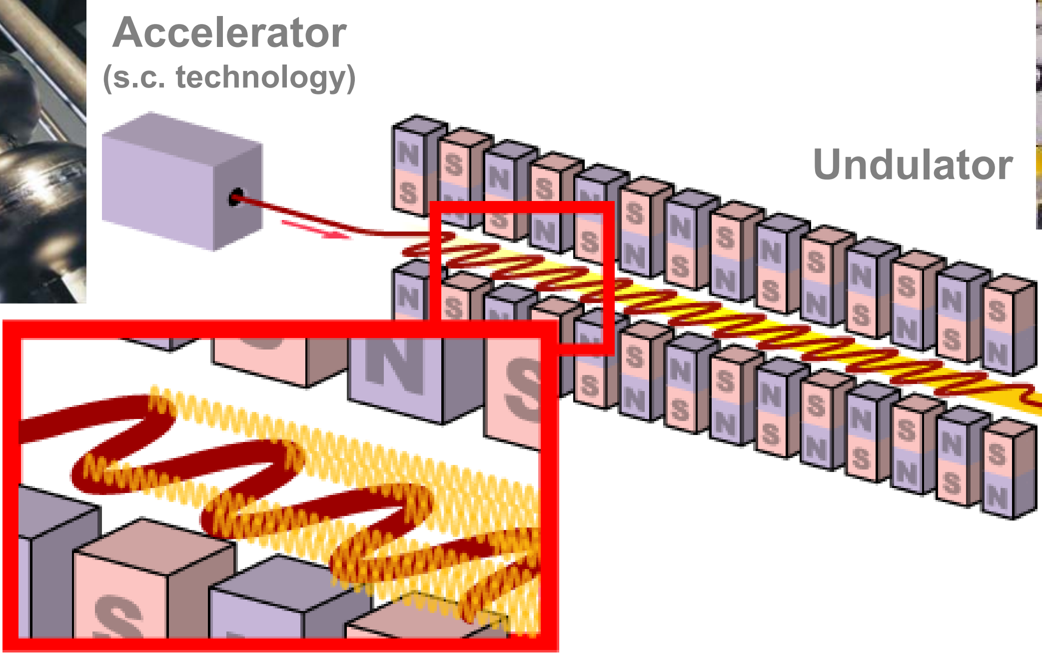
solve fundamental questions like

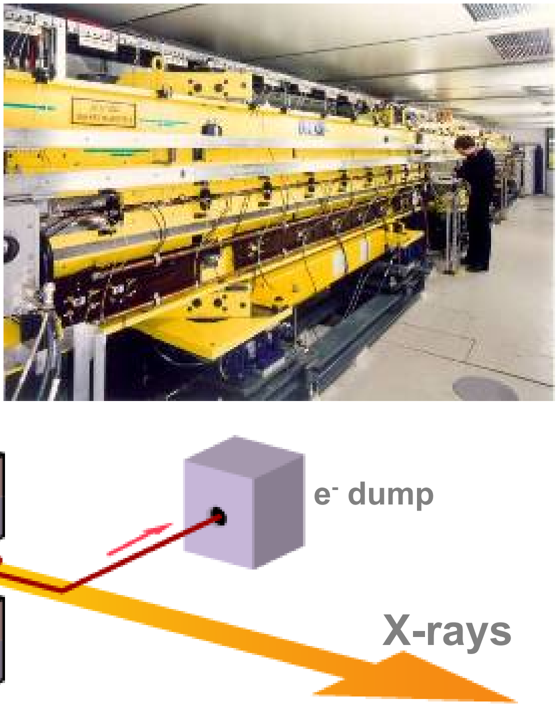
- origin of mass
- Higgs particle
- antimatter enigm
- …

→ now *ILC*



Principal layout of a (single pass) SASE FEL





FEL radiation is similar to synchrotron radiation, but

> wavelength tunable down to 1 Å → atomic scale resolution

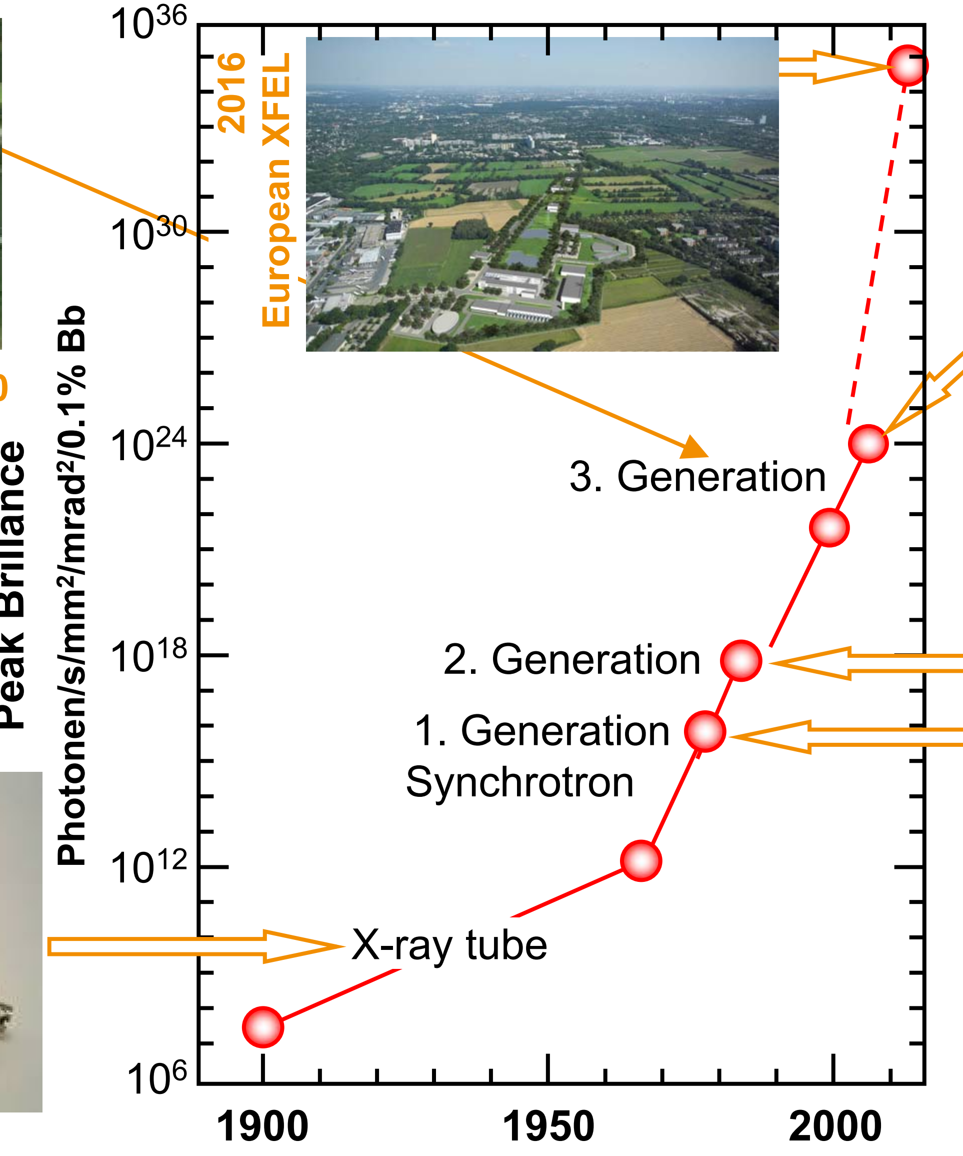
> ultra short pulses (fs scale) → molecular movies

> transverse spatial coherence → single nanoscale objects

> extremely high peak brilliance → matter under extreme conditions

FEL Peak Brilliance

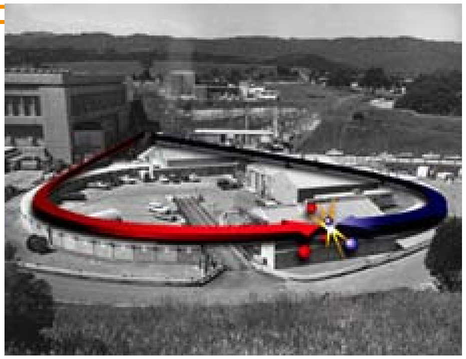
SLS (Villigen, CH) 2000



X-ray tube with rotating anode

ESRF (Grenoble, F) 1994

BESSY (Berlin, D) 1982

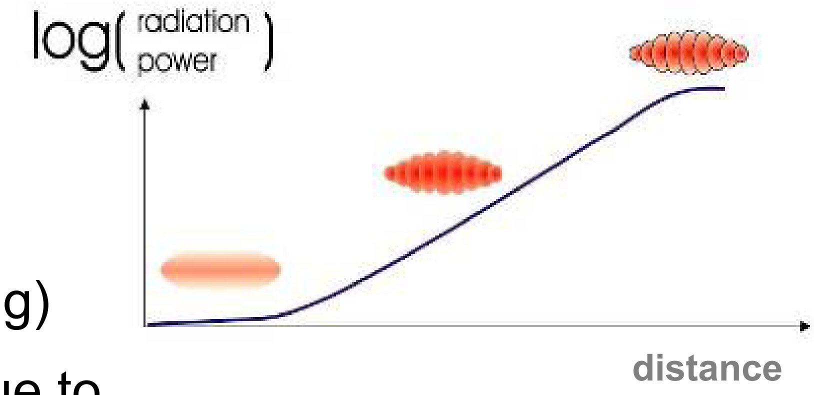


SPEAR (SLAC, USA) 1974

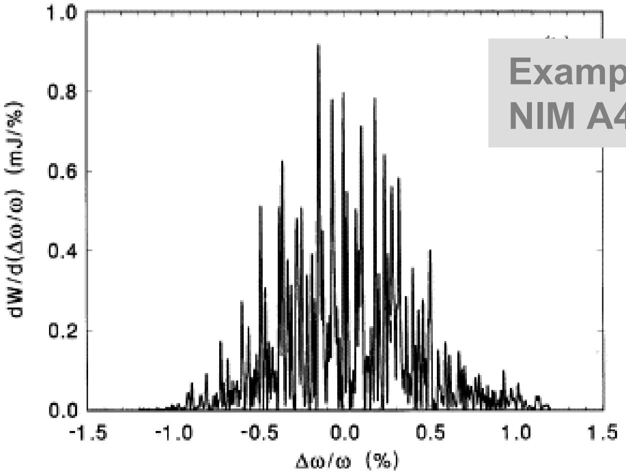
Courtesy R.Bakker

The SASE principle

- SASE = Self Amplified Spontaneous Emission
- electrons emit spontaneous radiation in the undulator
- emitted photons interact with the electrons:
  → energy modulation of the electrons
  → density modulation (micro-bunching)
- electrons in a slice radiate coherently
- exponential growth of radiation until saturation is reached (full micro-bunching)



Typical frequency spectrum: many lines due to start-up from noise



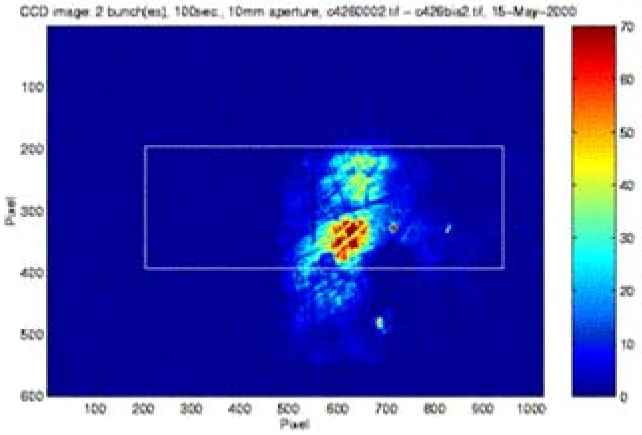
Example: TTF1 at 70 nm
NIM A429 (1999) 424-428

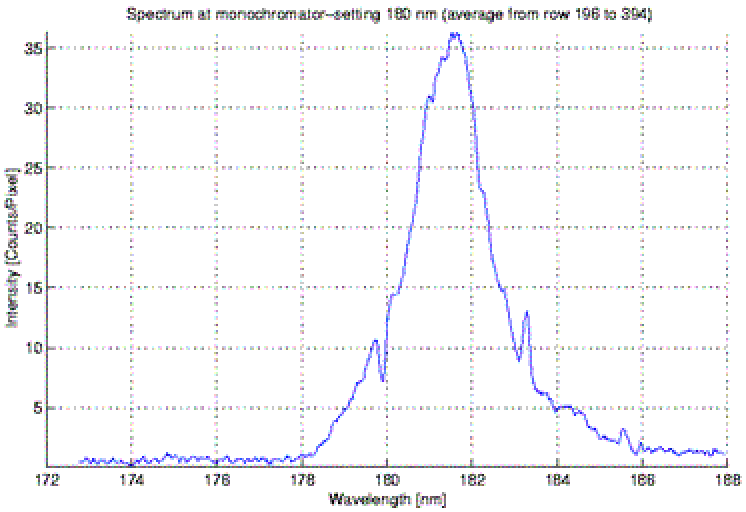
$$\lambda_\gamma = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

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

Operating SASE FELs

- > **TTF1** has demonstrated SASE in 2000 at 108.3 nm





- > **FLASH** runs as user facility since 2005, reaching ~4 nm
- > **LCLS** at SLAC provides wavelength down to 1.5 Å since 2009
- > **SCSS** at SPRing8 started commissioning down from 55 nm to 1 Å in 2011

- > many further (X-ray) FELs are planned world wide

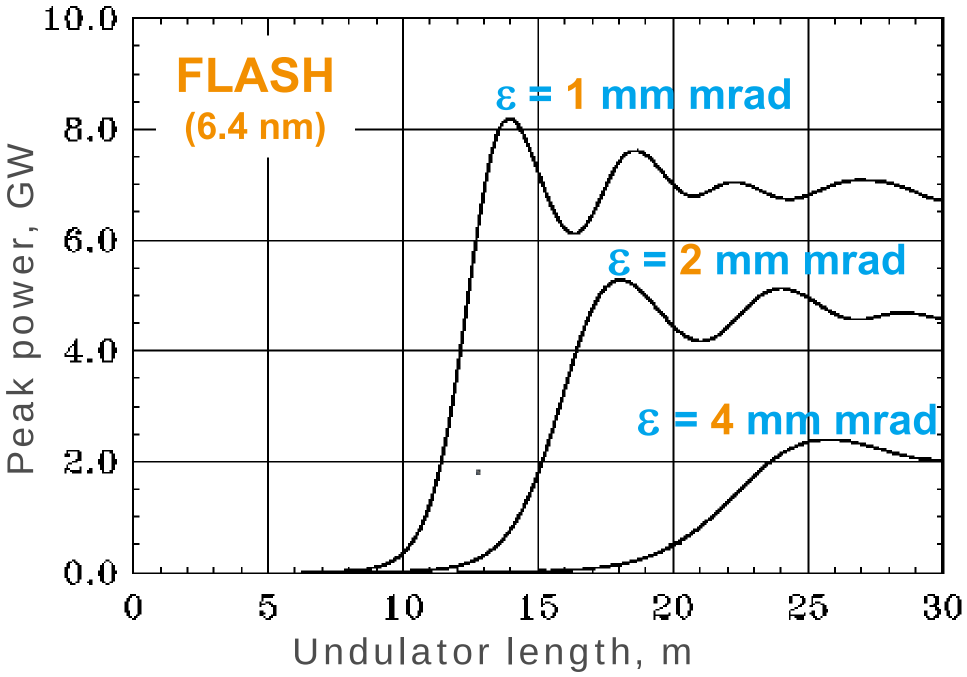
Status of the XFEL project

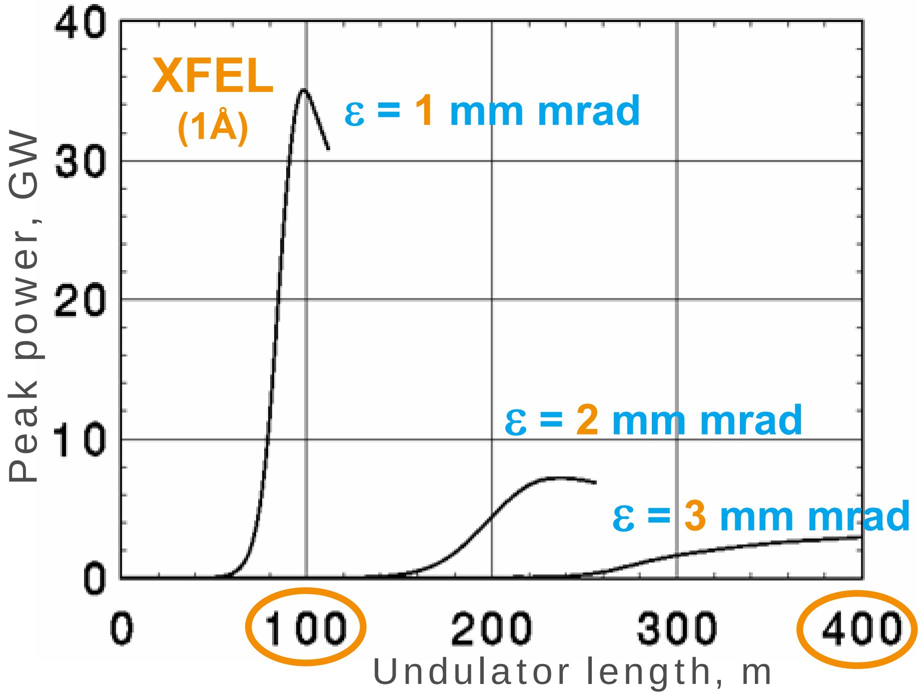
- The 3.3 km long X-ray Free Electron Laser facility was approved by the BMBF in 2003
- The project is being realized in European collaboration
- Current status:
  - Tunnel construction completed, infrastructure installations started
  - Injector installation (with gun from PITZ) will start in summer 2013
  - Commissioning of the accelerator in 2014
  - First X-rays (SASE) expected end of 2015


View of the experimental hall


Tunnel, Oct. 2012

FEL performance





- performance of an FEL depends strongly on the electron beam quality delivered by the injector, since beam quality degrades in the accelerator
- electron source must provide very small emittance electron beam

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

Goal emittance for the XFEL:
0.9 mm mrad @ injector, corresponding to
1.4 mm mrad @ undulator entrance

The PITZ project

Injector R&D became important to reach XFEL emittance requirements

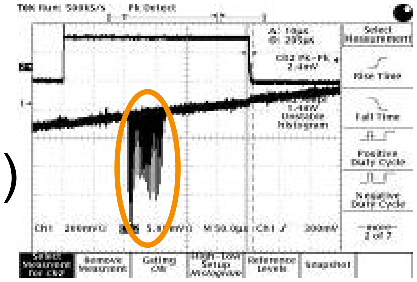
→ construction of a Photo Injector Test facility in Zeuthen with the goals:

- develop an electron source for the XFEL:
  - → very small transverse emittance (≤ 1 mm mrad @ 1 nC)
  - → stable production of short bunches with small energy spread
- extensive R&D on photo injectors independent of serving special user requests
- detailed comparison of experimental results with simulations:
  - → benchmark theoretical understanding of photo injectors
- prepare rf guns for subsequent operation at FLASH / XFEL
- test new developments (laser, cathodes, beam diagnostics)
- long term plans: e.g. flat beams, polarized electrons for ILC

Short PITZ history

- > 1999: decision to build PITZ
- > 2000: civil construction
- > 2001: infrastructure and first setup (PITZ1)
- > 13.1.2002: first photo electrons are produced
- > Nov. 2003: first optimized gun is sent to FLASH
- > 2005: continuous upgrade of the facility starts
- > 2007: first demonstration of XFEL requirements
- > 2009 - 2011: best emittance measurements (world record)


Dec. 2001




Feb. 2012

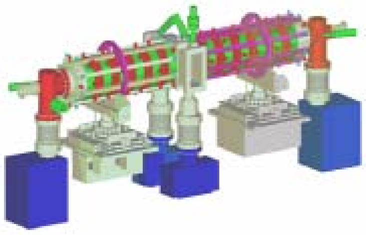
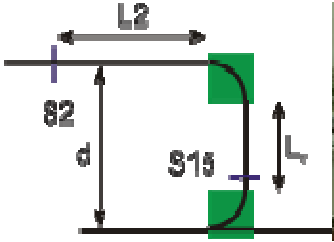

Feb. 2012

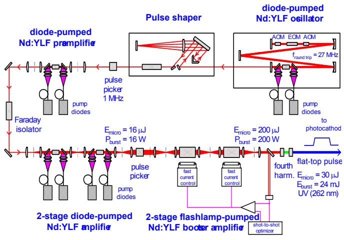
PITZ collaboration

- **BESSY Berlin**: ICTs, magnets, PS, vacuum expert
- **CCLRC Daresbury**: phase space tomography module
- **DESY Hamburg**: new cavities (guns, booster)
- **INRNE Sofia**: emittance measurement system (EMSY)
- **INR Moscow**: TDS (deflecting cavity)
- **INR Troitsk**: CDS booster cavity
- **LAL Orsay**: high energy spectrometers
- **LASA Milano**: cathode system
- **MBI Berlin**: laser system
- **TU Darmstadt**: beam dynamics simulations
- **Uni Hamburg**: bunch length measurement
- **YERPHI Yerevan**: accelerator controls




Funding through DESY (BMBF), HGF, EC (IA-SFS, EUROFEL)

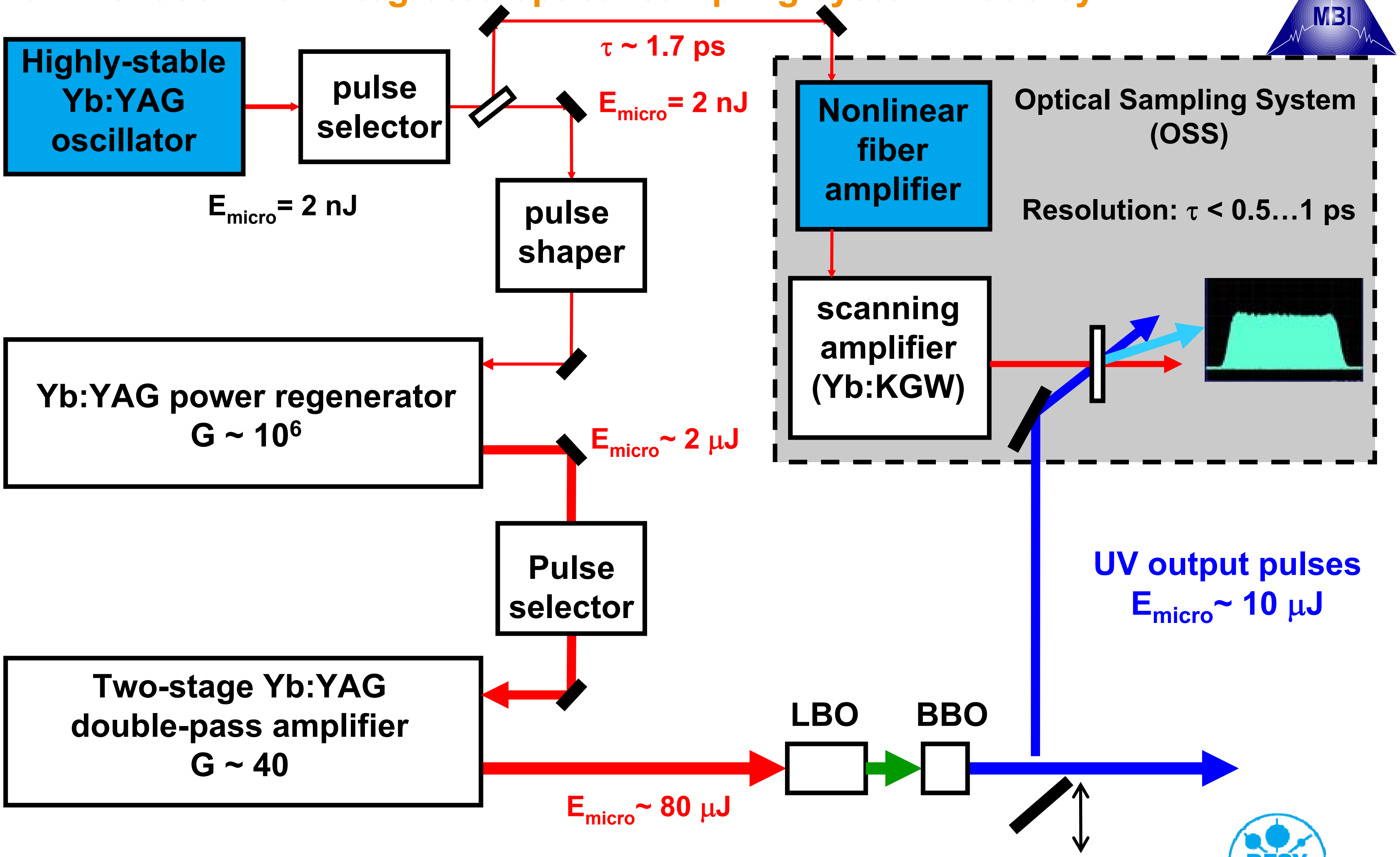



Continuous upgrade of subsystems

- **Laser system**:
  transverse and longitudinal distributions close to optimum case from simulations
- **Water cooling system**:
  improved cooling water temperature stability increases phase stability of the accelerating cavities
- **RF system**:
  improved RF regulation and phase stability due to the installation of an in-vacuum directional coupler at the gun, and setup of feedback algorithms
- **Gun cavities**:
  reduced dark current due to dry-ice cleaning (important for user operation); improved cooling channel design for higher average power
- **Booster cavities** (TESLA type / CDS type):
  increased beam energy allows for lower emittance
- **Diagnostics**:
  extension of the capabilities for detailed electron beam characterization

PITZ laser system: architecture

Yb:YAG laser with integrated optical sampling system made by MBI



Highly-stable Yb:YAG oscillator

E_{micro}= 2 nJ

pulse selector

τ ~ 1.7 ps

E_{micro}= 2 nJ

pulse shaper

Yb:YAG power regenerator
G ~ 10^6

E_{micro}~ 2 μJ

Pulse selector

Two-stage Yb:YAG double-pass amplifier
G ~ 40

E_{micro}~ 80 μJ

LBO

BBO

Nonlinear fiber amplifier

scanning amplifier (Yb:KGW)

Optical Sampling System (OSS)

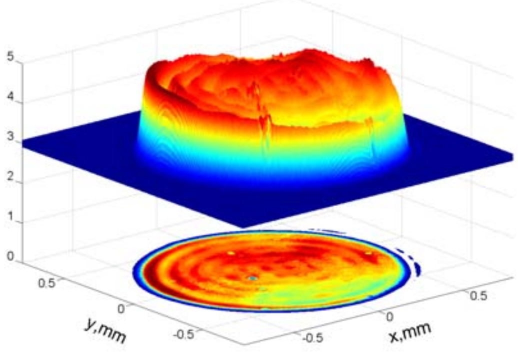
Resolution: τ < 0.5…1 ps

UV output pulses
E_{micro}~ 10 μJ

Laser profiles at the cathode plane

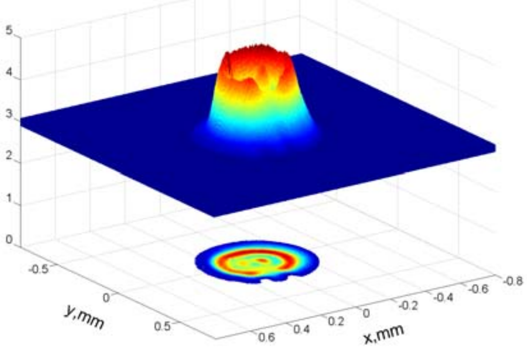
- > transverse profile: ~ flat-top
  Examples:

BSA=1.2mm (1nC)



σ_x=0.30 mm
σ_y=0.29 mm

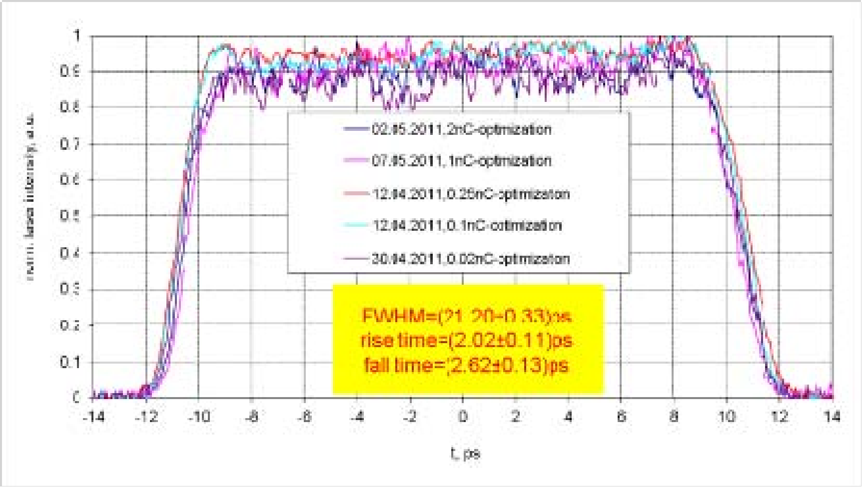
BSA=0.5mm (0.1nC)



σ_x=0.13 mm
σ_y=0.12 mm

(RMS sizes; no Gaussian fit!)

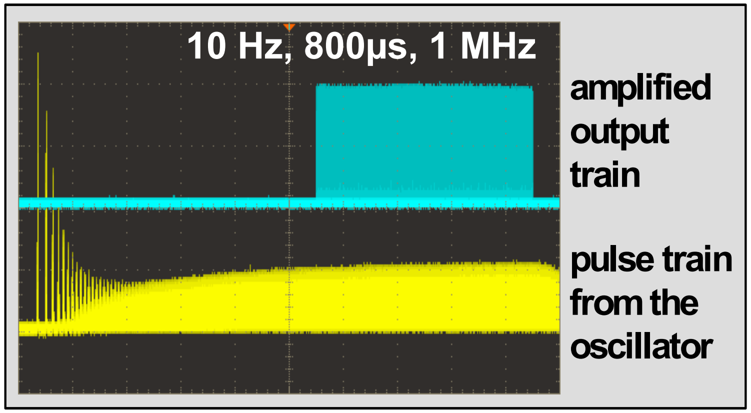
- > longitudinal profile: ~ 21 ps flat-top, 2-3 ps rise / fall times

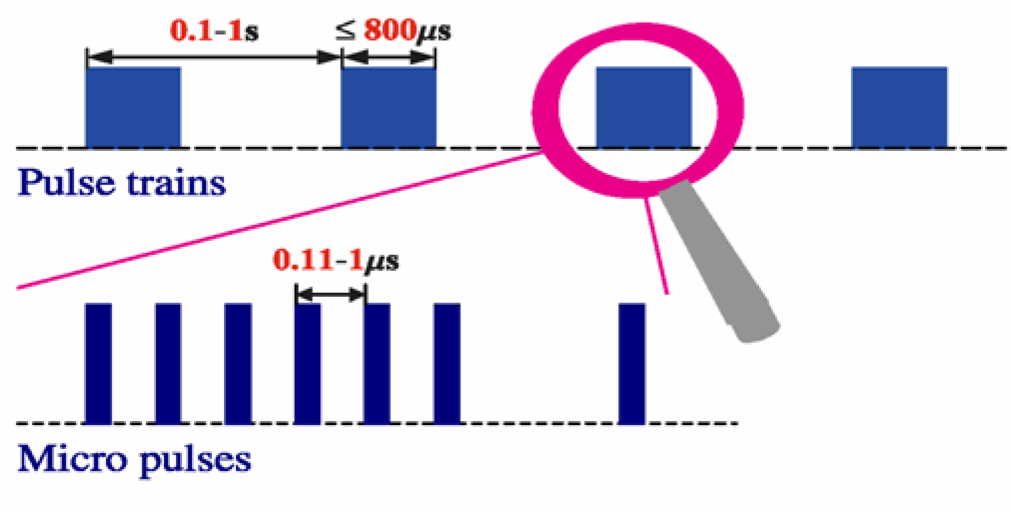


PITZ laser system: time structure

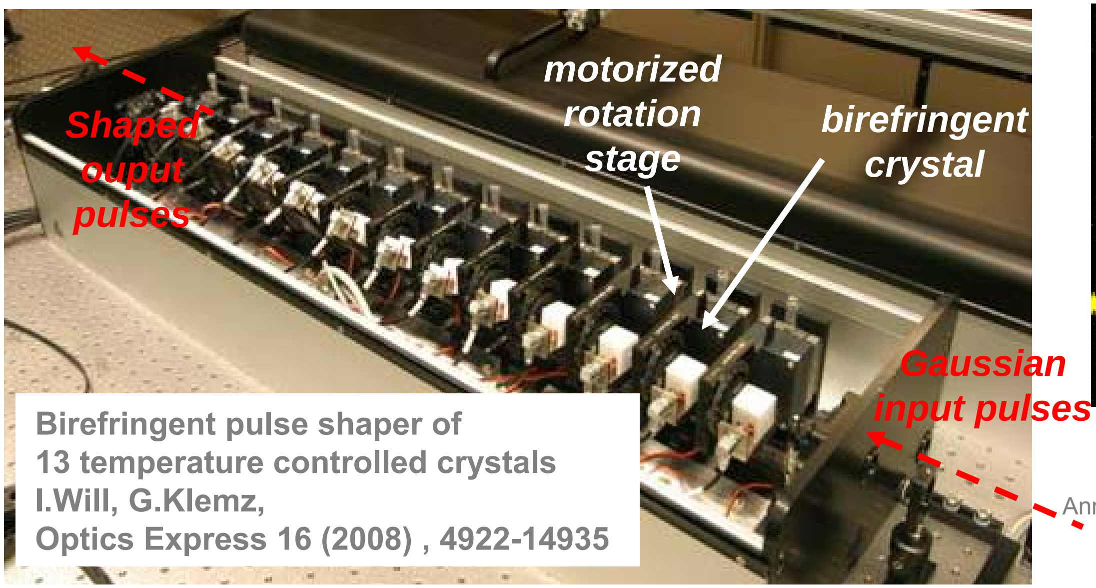
- using s.c. linac technology for FLASH / XFEL → long pulse trains needed

Pulse train structure:

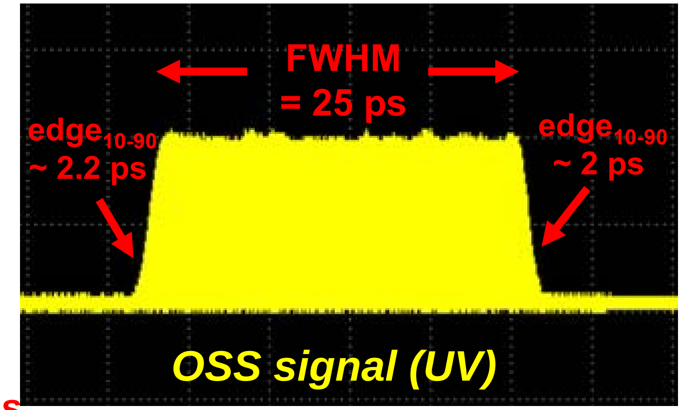




Micro pulse structure:

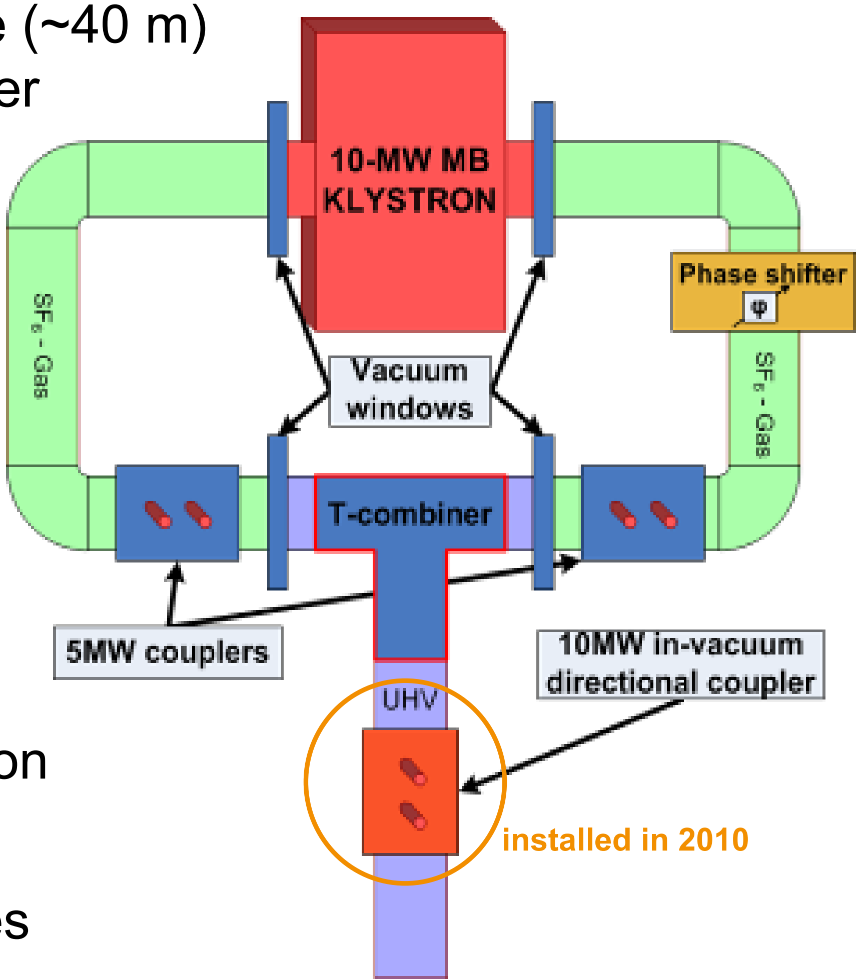


Birefringent pulse shaper of
13 temperature controlled crystals
I.Will, G.Klemz,
Optics Express 16 (2008) , 4922-14935



RF system and distribution

- 2 multi-beam klystrons, 2 arms, 5 MW each → 10 MW in total
- delivery system via long waveguide line (~40 m)
  → losses: < 8 MW arrive at gun / booster
- T-combiner combines power from both arms in front of the gun (booster has two power feeds)
- RF regulation acts on signals before the T-combiner (2x forward power, 2x reflected power)
  → exact power in the gun is unknown
- since 2010/11: 10 MW in-vacuum directional coupler used for RF regulation
  → improved regulation
- In addition: feedback algorithm improves phase stability significantly

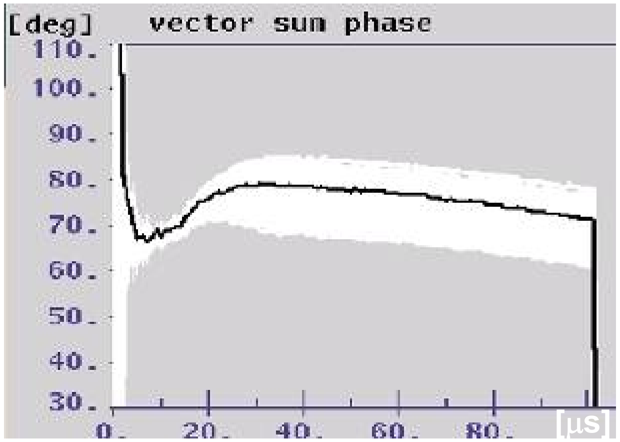


RF phase stability

2009 (no FB)

Reconstructed FPGA-Phase

based on the signals of
two 5 MW directional couplers



Phase change ~5 deg / 40 µs

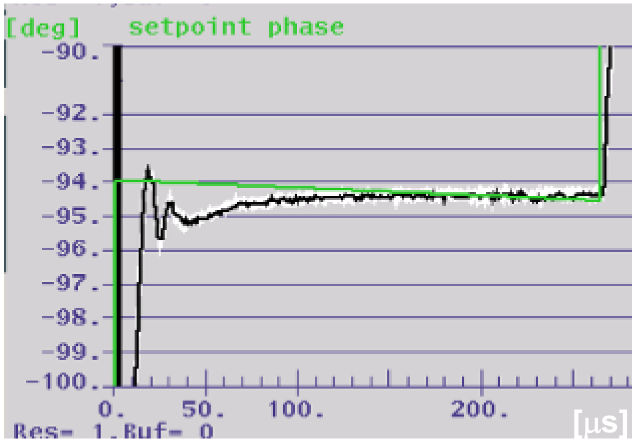
Phase jitter:

10-15 deg (peak-peak)
2-4 deg (rms)

2010/11 (FB on)

Measured FPGA-Phase

from the 10 MW directional coupler



Phase stays flat over the
full electron bunch train

Phase jitter:

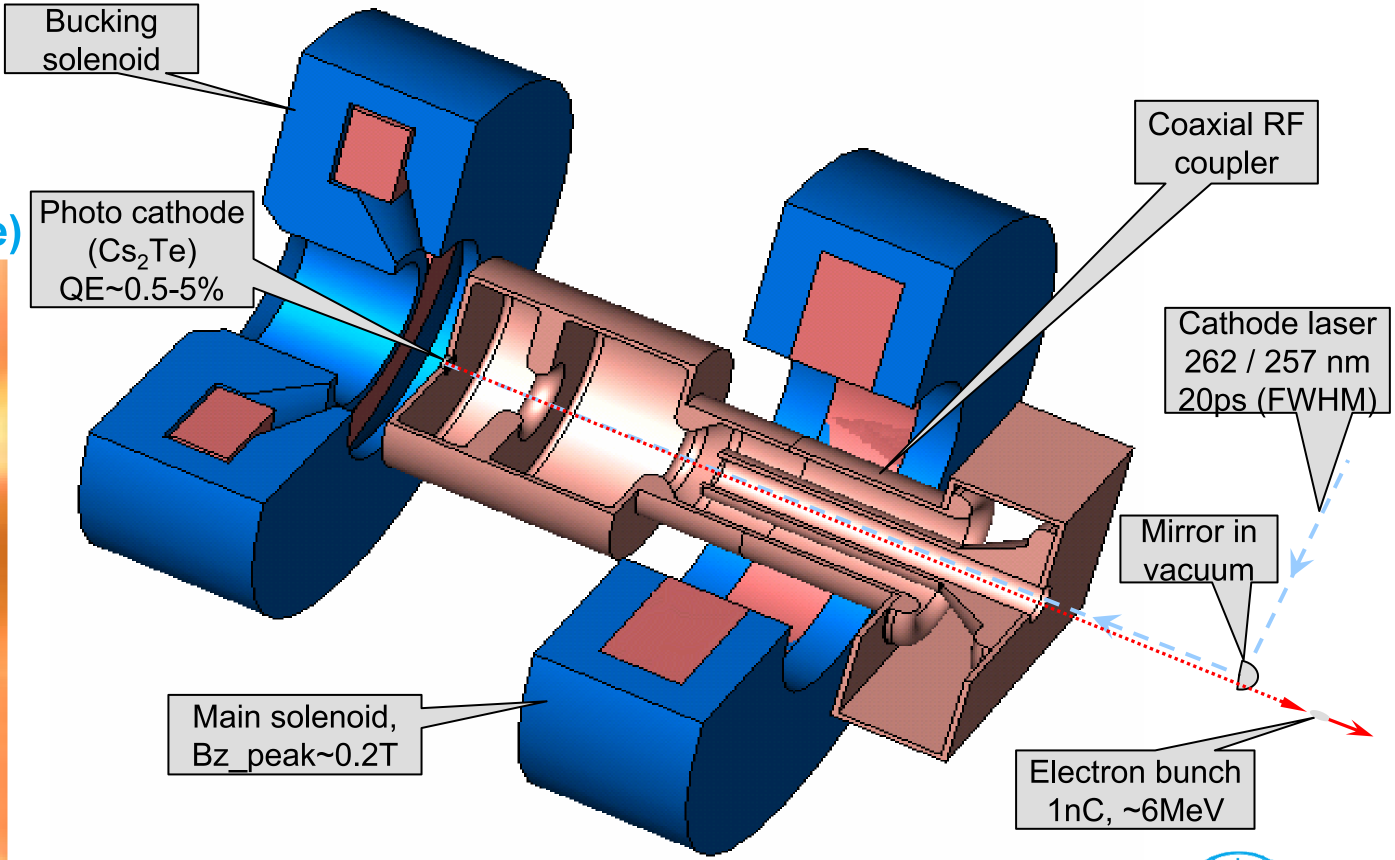
1-1.5 deg (peak-peak)
0.2-0.3 deg (rms)

The PITZ gun cavities

1.3 GHz 1.5 cell photo cathode RF gun

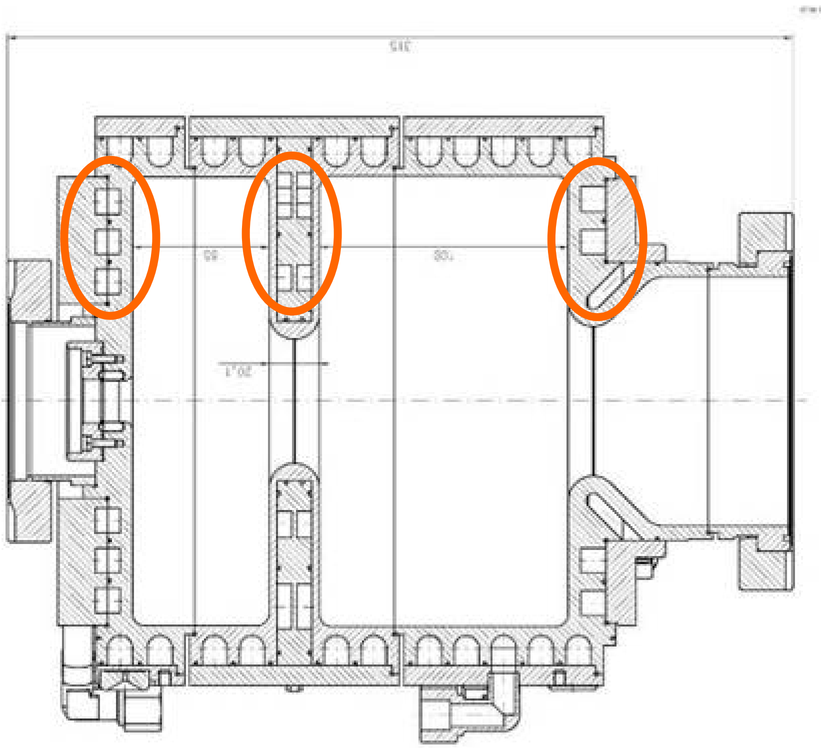
- **capable of high average power → long electron bunch trains (s.c. linac)**
- **delivers very low normalized transverse emittance**

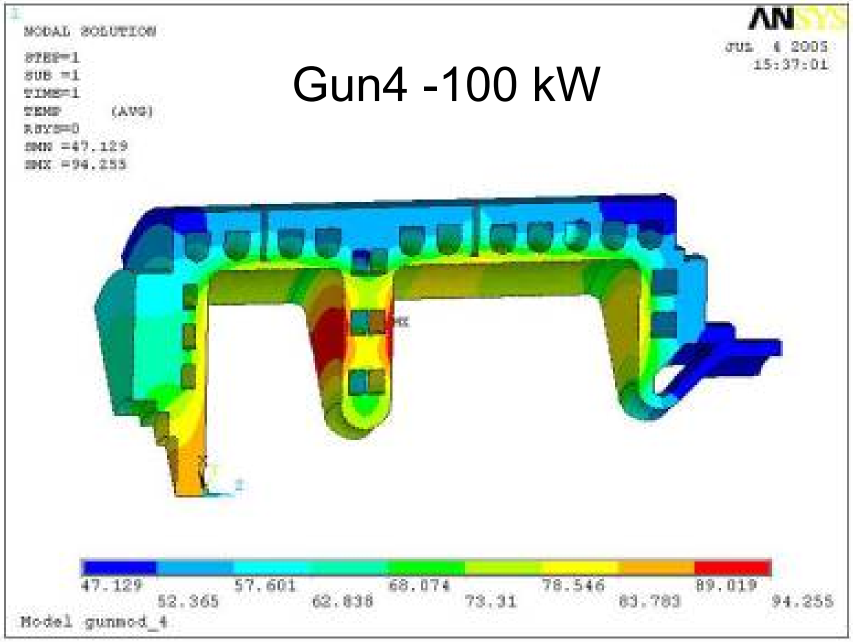
View through the full cell onto iris and backplane (with cathode)



Gun development

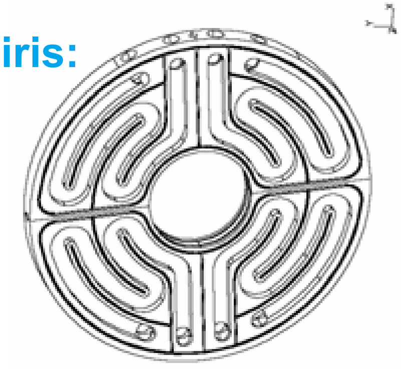
Gun4 design: improved cooling for higher average power





Gun4 -100 kW

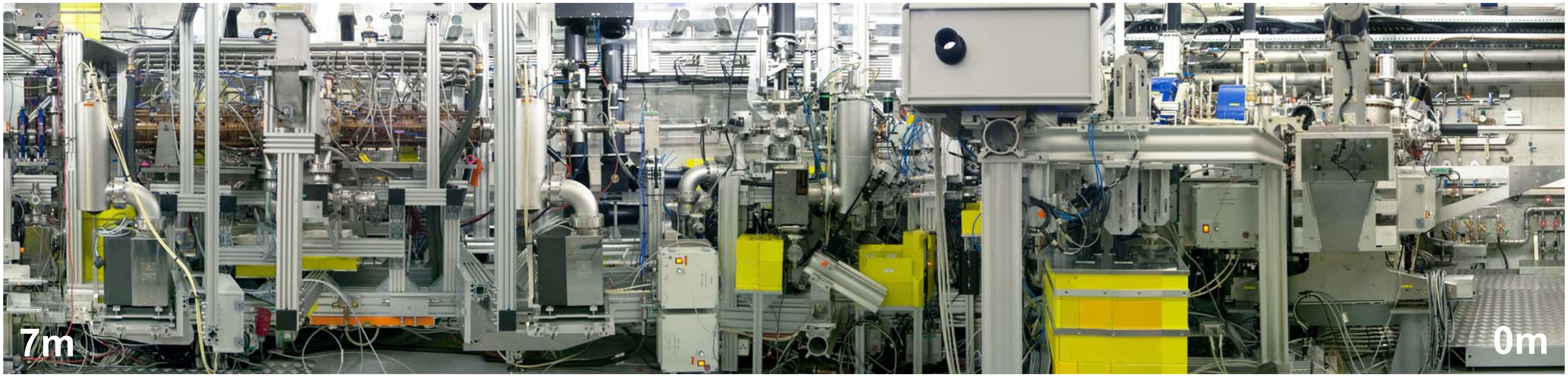
Cut through the iris:

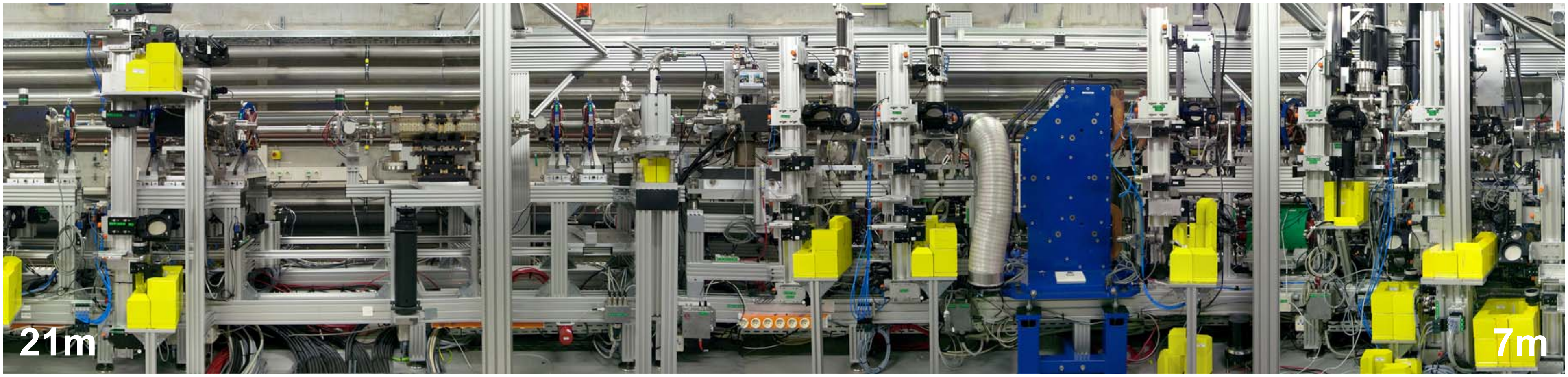


Courtesy J.Meißner

The PITZ diagnostics beamline (PITZ1.8 setup)

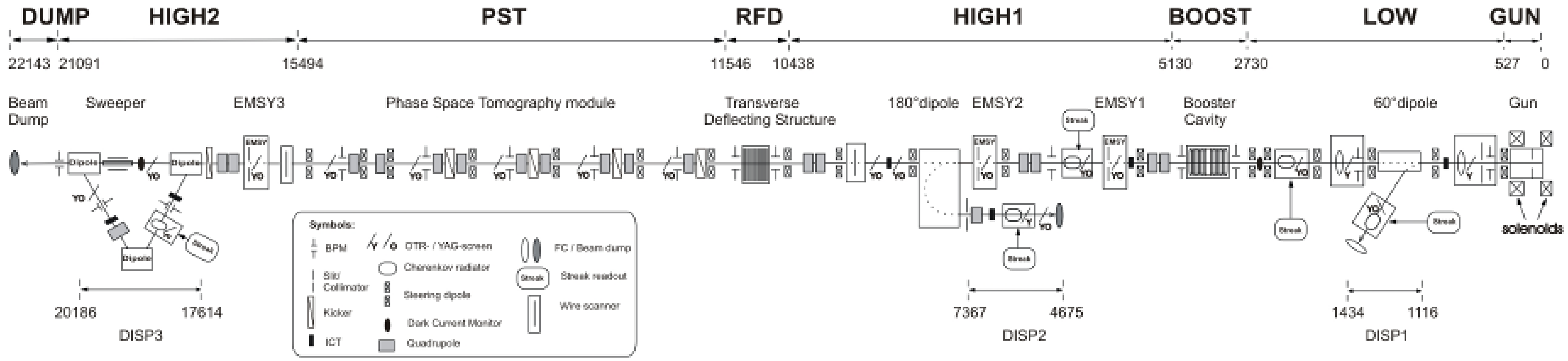
Status summer 2011





Electron beam characterization with PITZ2

Scheme of the PITZ2 setup:



- bunch charge: Faraday Cups, ICTs
- beam size: YAG screens
- momentum and momentum spread: spectrometer
- bunch length: aerogel / quartz + streak camera,
  later also RF deflector (TDS)
- emittance (thermal, projected, slice)
  with EMSYs, quads, tomographic section (PST)
- …

Emittance measurements at PITZ

Longitudinal emittance:

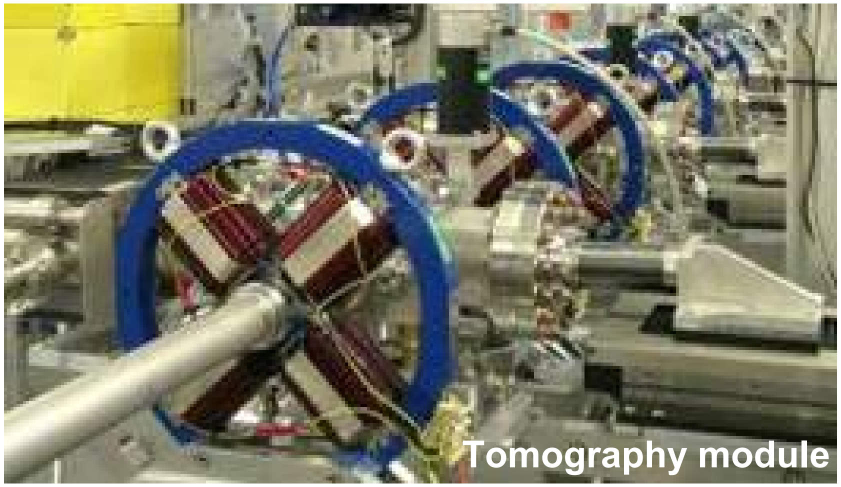
- bunch length measurements
- bunch energy spread measurements

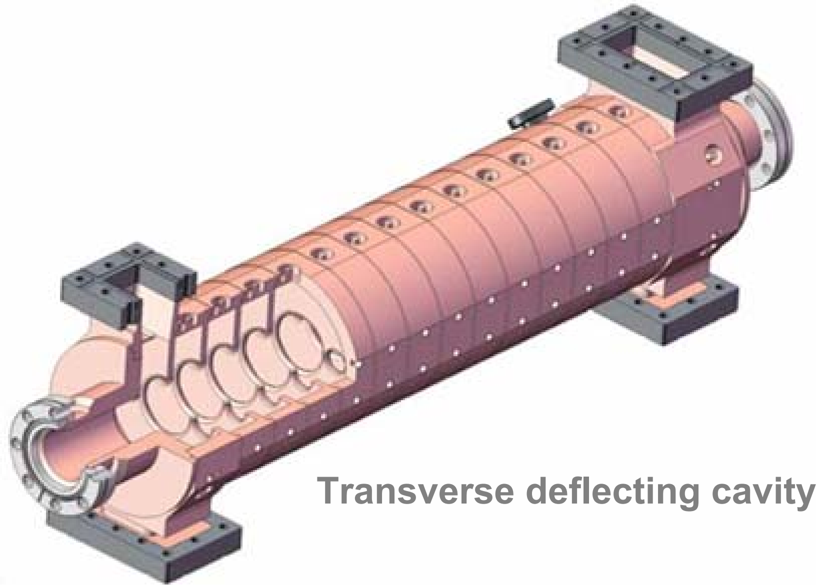
Transverse Projected Emittance:

- slit scan method (main method at PITZ)
- quad(s) scan
- transverse phase space tomography

Transverse slice emittance:

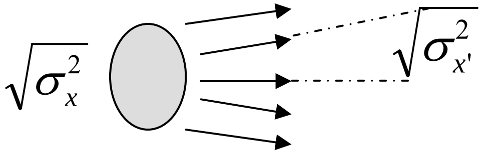
- booster off-crest + spectrometer
- upcoming: RF deflector


Tomography module


Transverse deflecting cavity

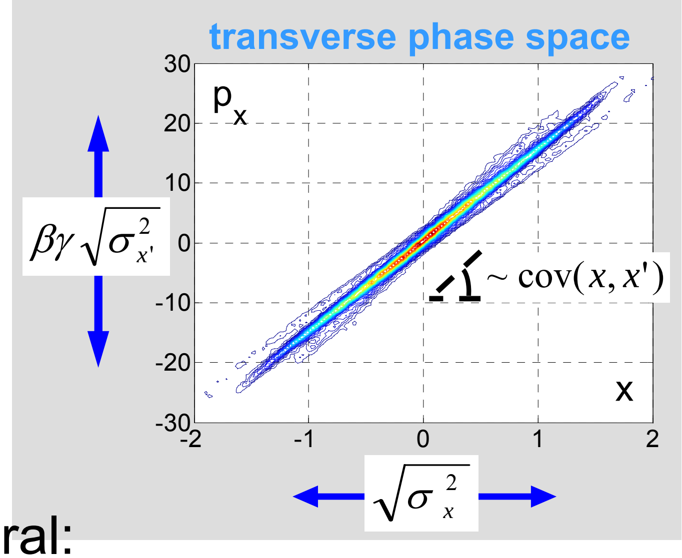
Emittance concept

- > ε = 6D phase space volume occupied by a given number of particles
- > Longitudinal emittance: ε_z ~ (bunch length) • (bunch energy spread)
- > Transverse emittance: $\varepsilon_{x,y}$ ~ (beam size) • (beam angular divergence)



- > Effect of acceleration on emittance: adiabatic damping (reduction of angular divergence)

$$\beta \bullet \gamma \bullet \sqrt{\sigma_{x'}^2}$$



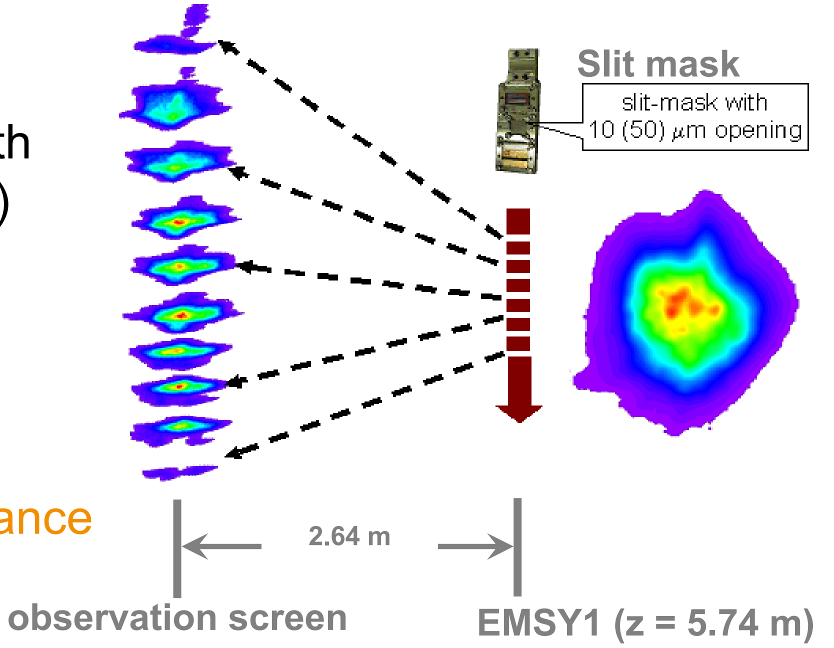
- > Normalized emittance ε^n is conserved in general:

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

Courtesy F.Stephan

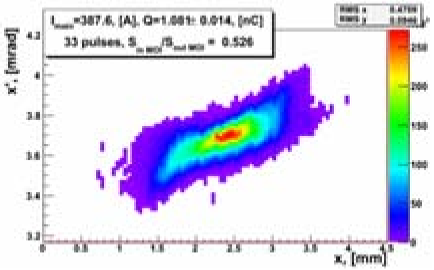
Emittance measurement procedure: principle

- Emittance Measurement System consisting of horizontal / vertical actuators with YAG / OTR screens and slits (50 μm / 10 μm)
- single slit scan technique is applied
- measurement procedure is under permanent improvement
- as conservative as possible: 100% rms emittance



Procedure:

- beam size $\sqrt{\sigma_x^2}$ is measured @ slit position using screen
- beam local divergence $\sqrt{\sigma_{x'}^2}$ is estimated from beamlet sizes @ observation screen (12 bit camera)

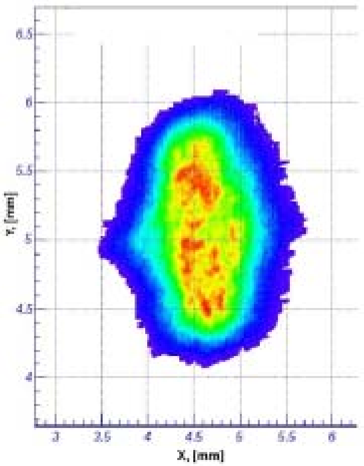


N.B.: measured emittance numbers are permanently reducing as a result of machine upgrades and extensive optimization:

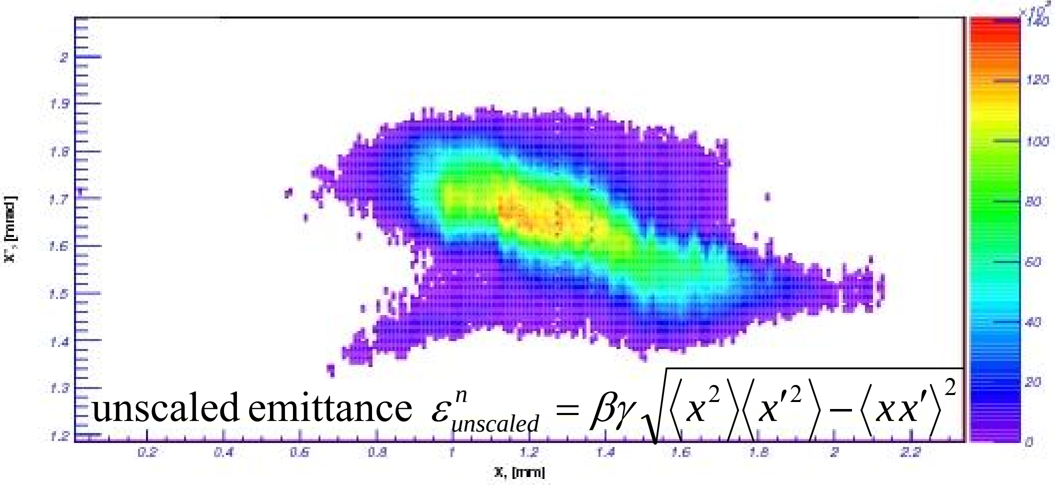
"We are measuring more and more of less and less…"

Emittance measurement procedure: scaling

measured beam at EMSY screen



measured transverse phase space

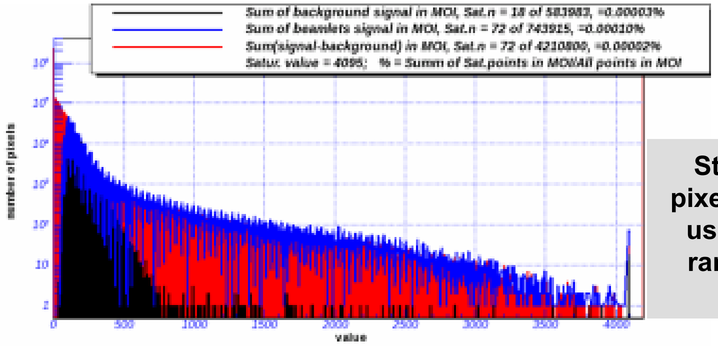


unscaled emittance $\varepsilon^n_{unscaled} = \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$

σ_x ← x-projection $\neq$ x-projection → $\sqrt{\langle x^2\rangle}$

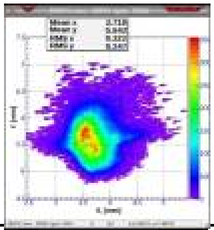
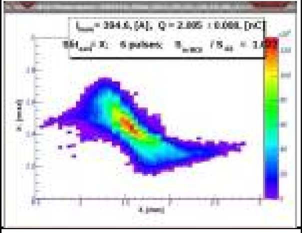
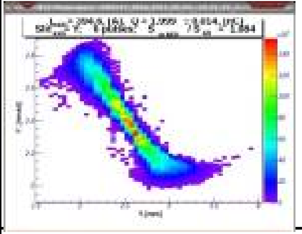
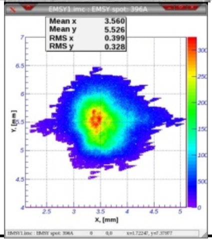
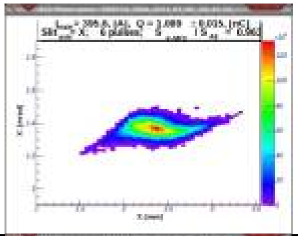
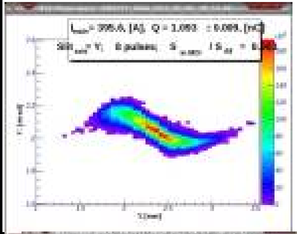
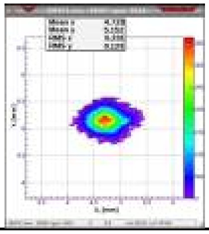
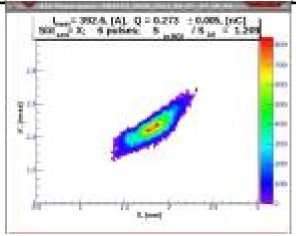
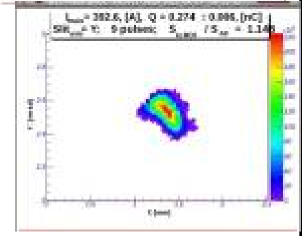
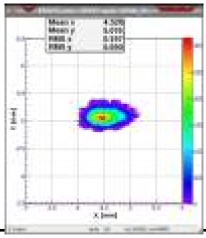
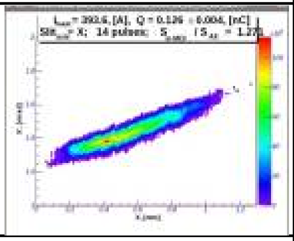
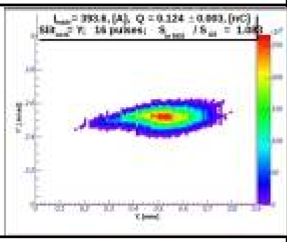
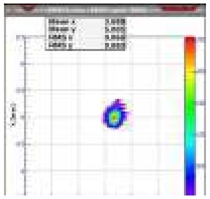
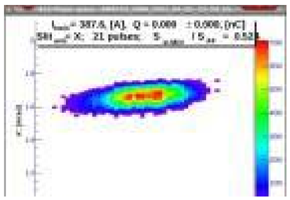
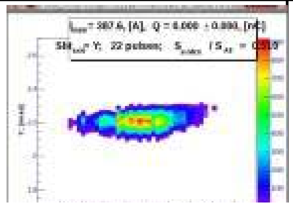
scaled emittance $\varepsilon^n_{scaled} = \dfrac{\sigma_x}{\sqrt{\langle x^2\rangle}}\beta\gamma\sqrt{\langle x^2\rangle\cdot\langle x'^2\rangle - \langle xx'\rangle^2}$

scale factor (>1) corrects for underestimation of the beamlet size due to low intensity losses



Statistics over all pixels in all beamlets using full dynamic range of the 12-bit camera

Emittance measurements: examples

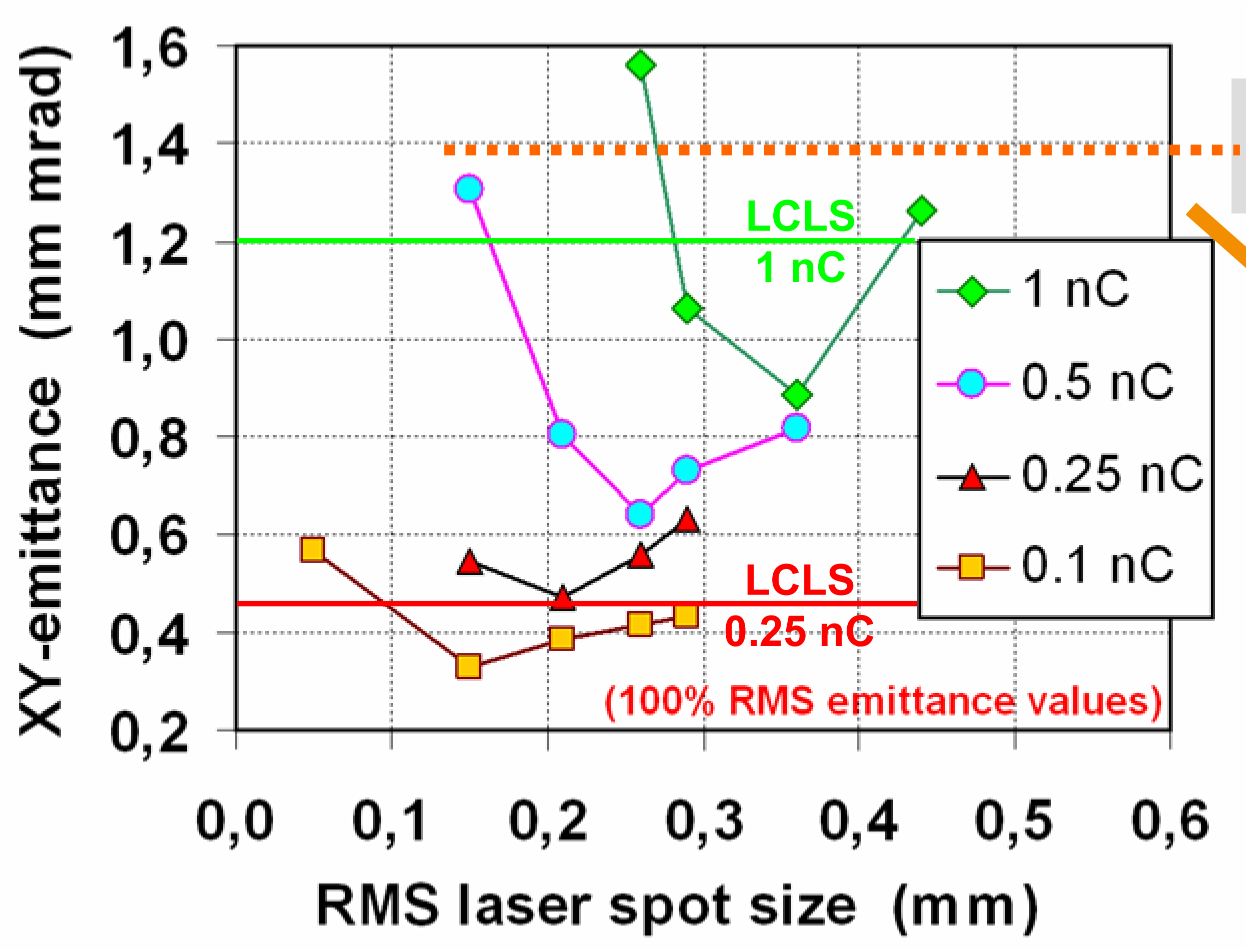
Qbunch / Las.XYrms	Beam at EMSY1		Horizontal phase space		Vertical phase space		ϕ_{gun}
	XY-Image	σ_x / σ_y		ε_x		ε_y	
2 nC **0.38 mm**		0.323mm 0.347mm		1.209 mm mrad		1.296 mm mrad	+6deg
1 nC **0.30 mm**		0.399mm 0.328mm		0.766 mm mrad		0.653 mm mrad	+6deg
0.25 nC **0.18 mm**		0.201mm 0.129mm		0.350 mm mrad		0.291 mm mrad	0deg
0.1 nC **0.12 mm**		0.197mm 0.090mm		0.282 mm mrad		0.157 mm mrad	0deg
0.02 nC **0.08 mm**		0.066mm 0.083mm		0.111 mm mrad		0.129 mm mrad	0deg

zoomed

Courtesy M.Krasilnikov

Emittance measurement results 2009

Reaching XFEL beam quality (TESLA booster, bad phase stability)



XFEL (1 nC) slice emittance requirement at the undulator

these results + experience from LCLS (only small degradation of slice emittance from gun towards undulator)

➡ **XFEL can be operated with 14 GeV beam energy**
(possibility to save ~33M€)

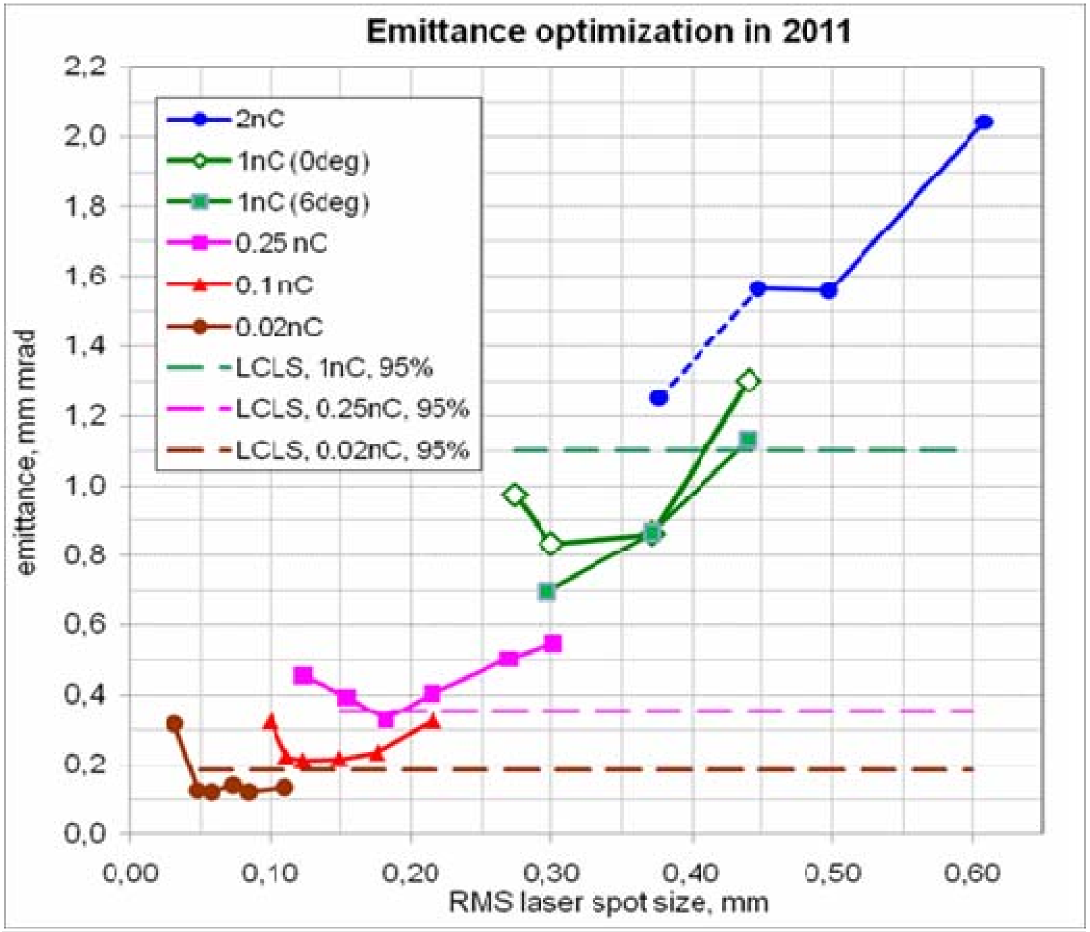
Emittance measurement results 2011

Improvements due to

- higher beam energy (CDS booster: 25 MeV)
- better laser profile
- significantly improved phase stability
- reducing magnetic fields

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 long pulse train operation and using full dynamic range of 12-bit camera for beamlet detection



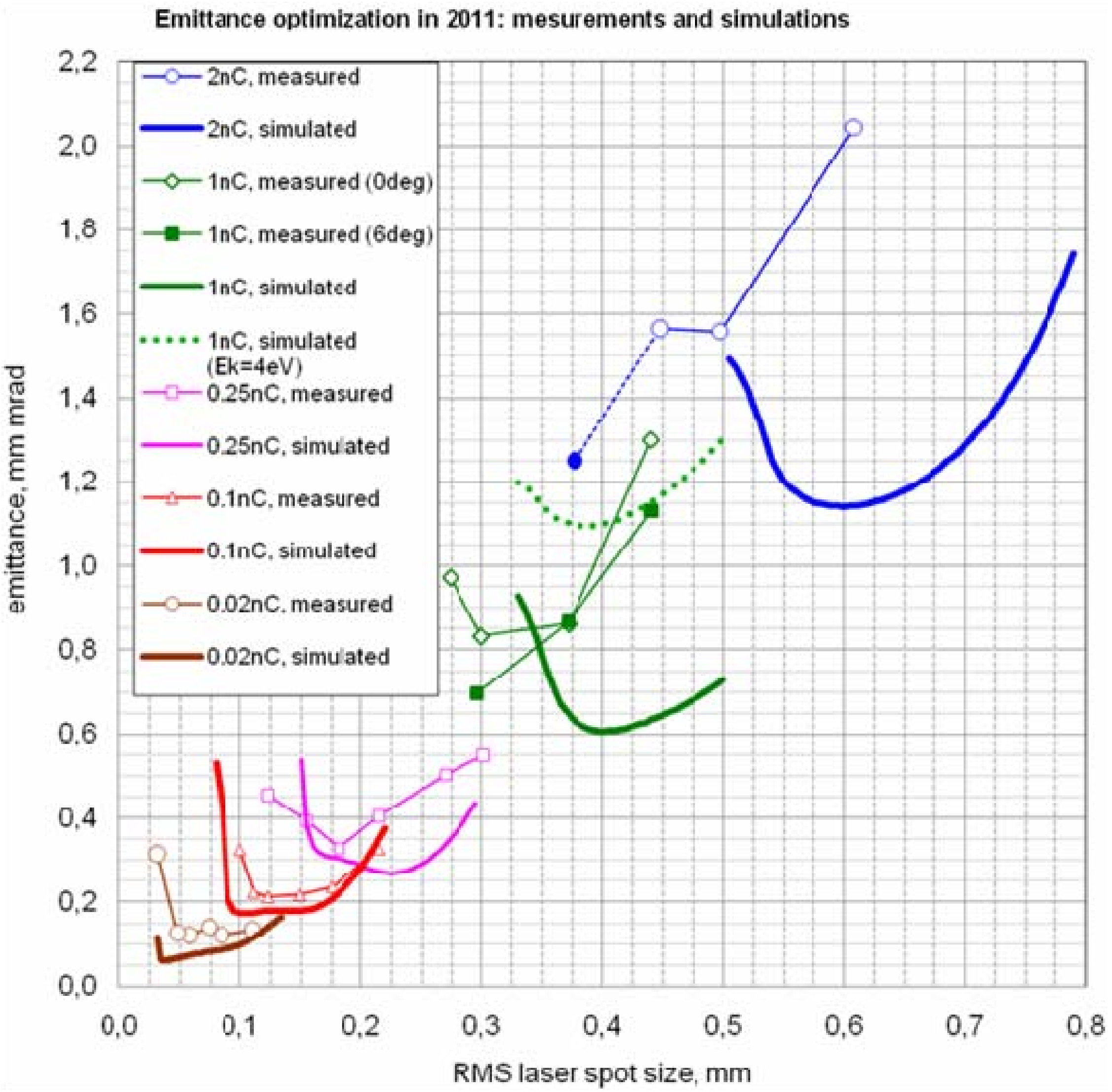
LCLS data:
P. Emma, "Beam Brightness Measurements in the LCLS Injector“, Mini-WS on compact XFELs using HBB, LBNL, Berkeley, USA, 2010.
J. Frisch, "Operation and Upgrades of the LCLS", LINAC2010, Tsukuba, Japan.

Courtesy F.Stephan

Measurements vs. Simulation (2011 data)

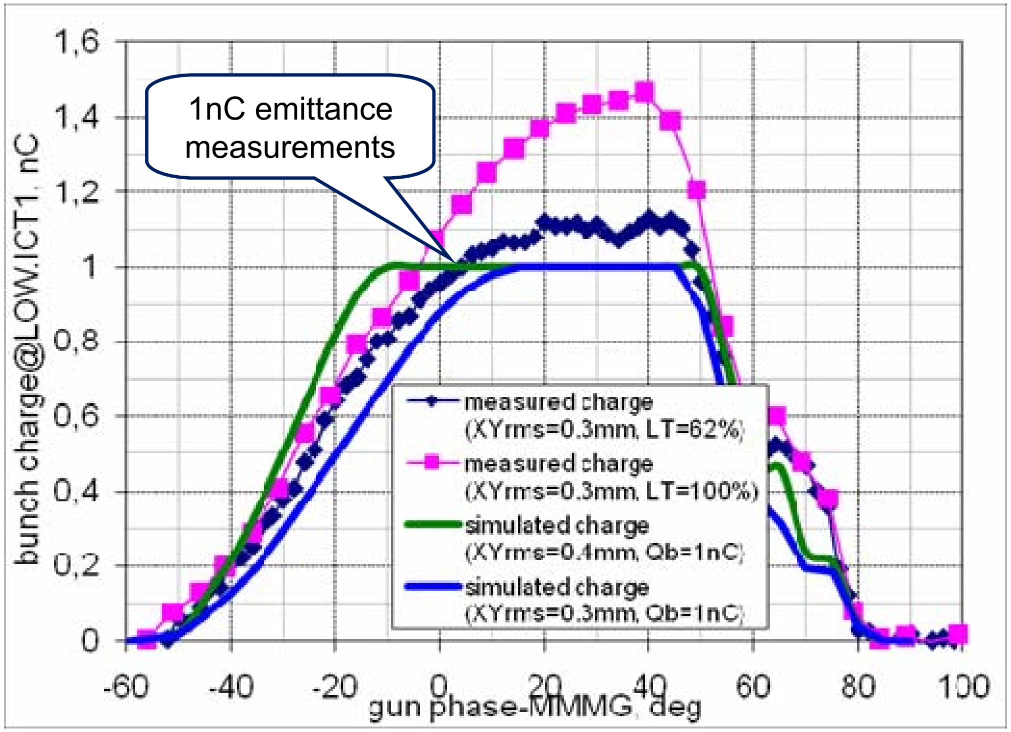
Emittance optimization

- for each bunch charge, the photo injector has been optimized in experiment and in simulations while keeping the temporal laser profile fixed (21.5ps FWHM, 2ps rise/fall time)
- simulated optimum machine parameters do not agree with the experimentally obtained ones (e.g. gun phase, laser spot size)
- differences are smaller for small charges (e.g. for 100 pC good agreement in all distributions for simulation and experiment)
- differences could explained by modeling problems of the photo emission process



Simulation of the photo emission process

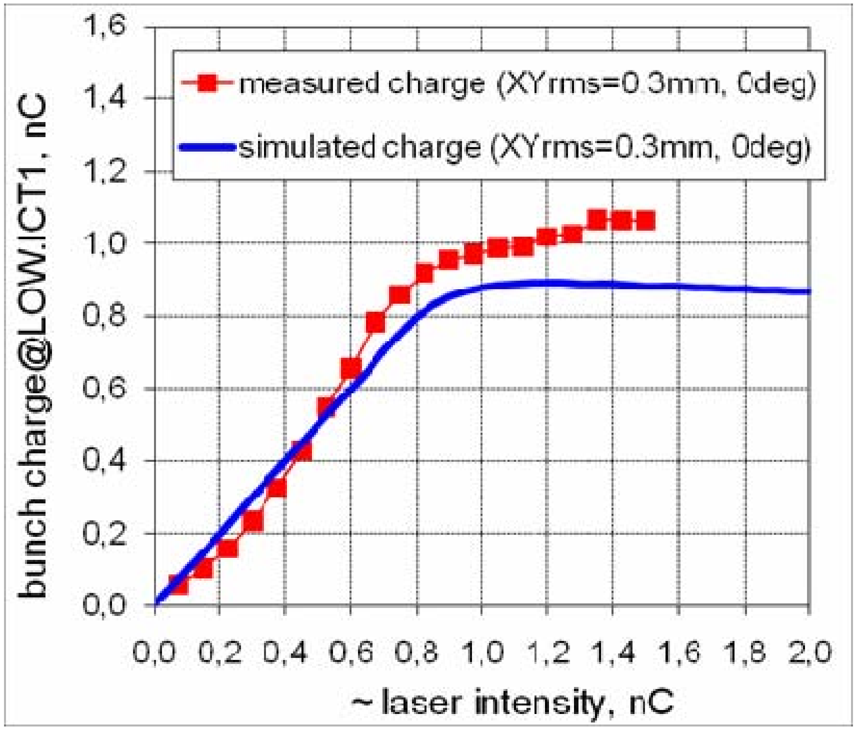
Measured and simulated Schottky scans (1nC)



- direct plug-in machine settings into ASTRA does not produce 1nC at the gun operation phase (+6deg), whereas 1nC and even higher charge (~1.2nC) are experimentally detected
- simulated (ASTRA) phase scans w/o Schottky effects (solid thick lines) have different shapes than the experimentally measured (thin lines with markers)

→ Photo emission (bunch charge) needs more detailed modeling in simulations.

Measured and simulated laser energy scan (1nC)



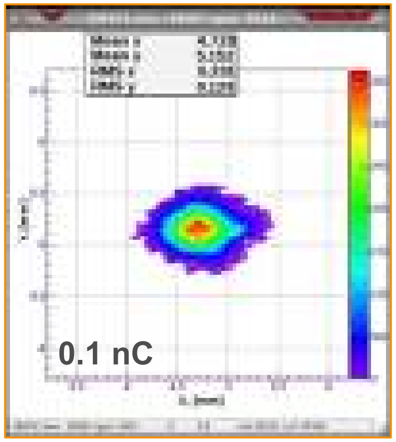
- laser intensity (LT) scan for the MMMG phase (red curve with markers) shows higher saturation level, whereas the simulated charge even goes slightly down while the laser intensity (bunch charge) increases

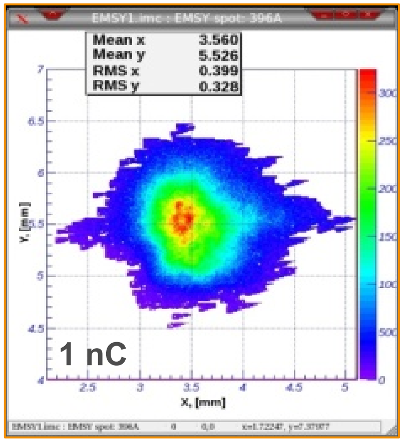
Courtesy M.Krasilnikov

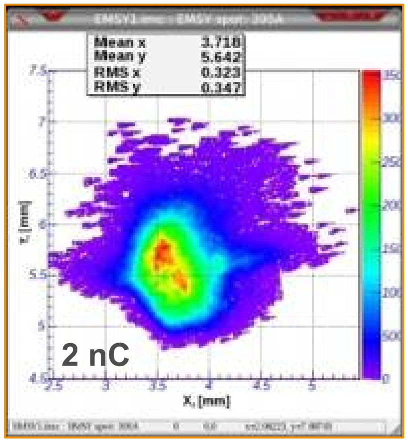
Further discrepancies

> Tails in the beam distribution:

- obviously X-Y asymmetry in the beam (~horizontal)
- Mainly for space charge dominated beams (high bunch charge)
- large emittance scaling factor (beamlets from tails are not detectable)







> Possible reason: magnetic fields along the beamline

- remaining magnetizable components, mainly in the low energy section
- solenoid imperfections
- stray fields from vacuum pumps (IGP)
- …

Summary

> Development of high brightness electron sources at PITZ

  - specs for the European XFEL have been demonstrated and even surpassed (normalized emittance <0.9 mm mrad at 1nC)
  - PITZ serves also as a benchmark for theoretical understanding of the photo injector physics (beam dynamics simulations vs. measurements)

> Emittance measurements procedure

  - nominal method: single slit scan for detailed phase space reconstruction
  - as conservative as possible; scaling procedure → 100% rms emittance
  - continuous improvement of the procedure

> Emittance measurements at PITZ:

  - Beam emittance has been optimized for a wide range of bunch charges (20pC; 100pC; 250pC; 1nC; 2nC)
  - emittance ~ linearly on the bunch charge
  - rather good agreement between measured and simulated emittance values

> Open problems:

  - optimum machine parameters: simulations ≠ experiment
  - emission (charge production) from experiment is not straightforward reproduced by simulations
  - tails in X-Y distributions especially for highly space charge dominated beams
  - gun temperature stability is still to be improved (to reach the HH level of 0.006deg)
  - …