Diagnostic Systems for Characterizing Electron Sources at the Photo Injector Test Facility at DESY, Zeuthen site

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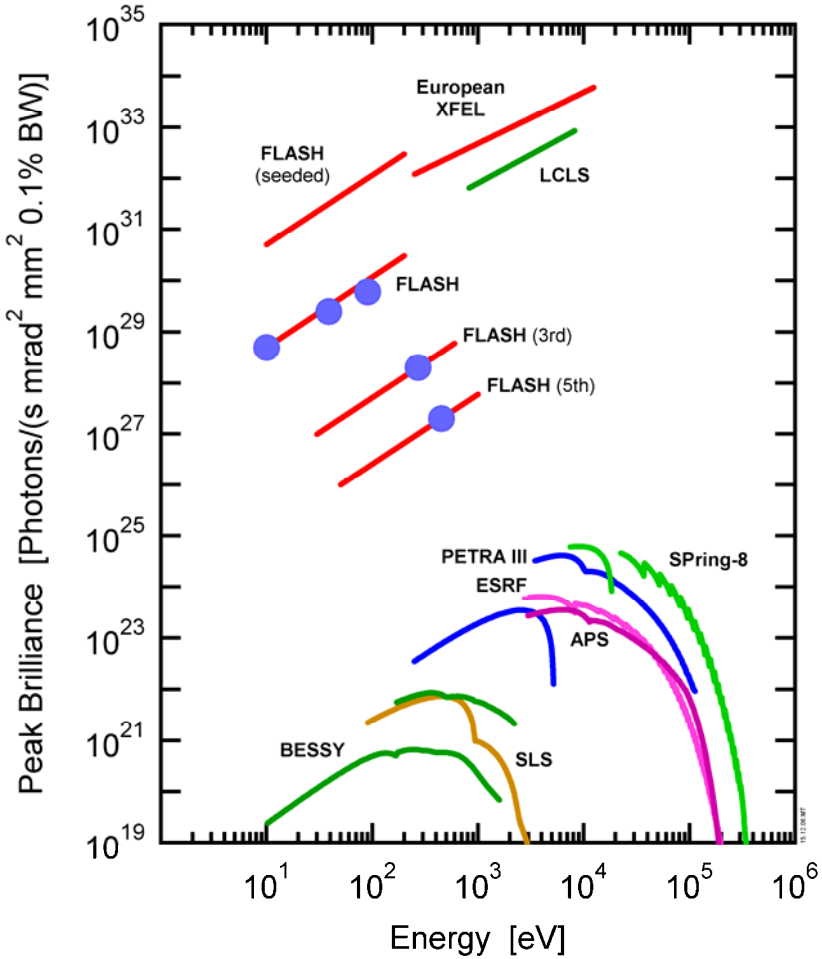
(on behalf of the PITZ team)

- Motivation
- Photo Injector Test Facility at DESY in Zeuthen (PITZ)
- Components & beam diagnostics
- Experimental results
- Summary

Motivation: European XFEL – a next generation light source

Goal parameters of the European-XFEL

- Short wavelength down to 0.1 nm
- High peak and average brilliance
  → investigations of matter under extreme conditions
- Ultra-short pulses (≤ 100 fs)
  → high temporal resolution to study ultra-fast dynamics e.g. molecular movies
- Transverse spatial coherence
  → imaging study of single nano-scale objects (no crystallization needed)

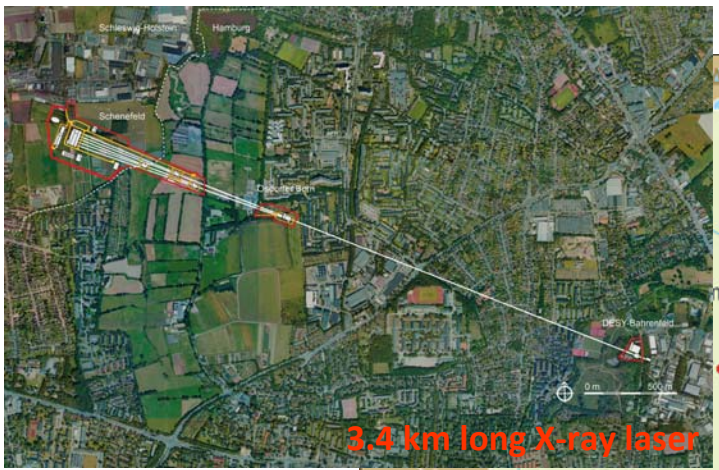


Goal parameters of the European XFEL can only be reached with high quality electron beams at the undulator entrance!

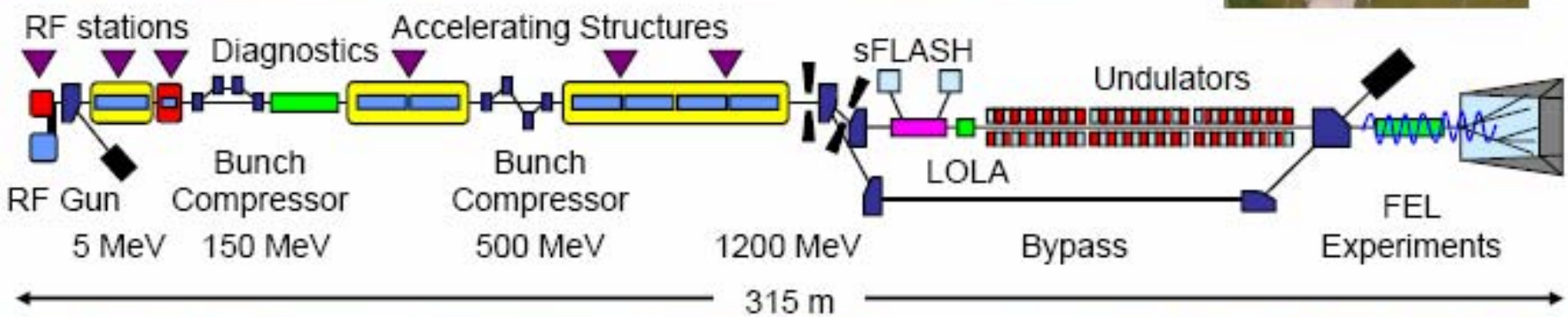
Deutsches Elektronen-Synchrotron (DESY)

Free-Electron Lasers @ DESY:

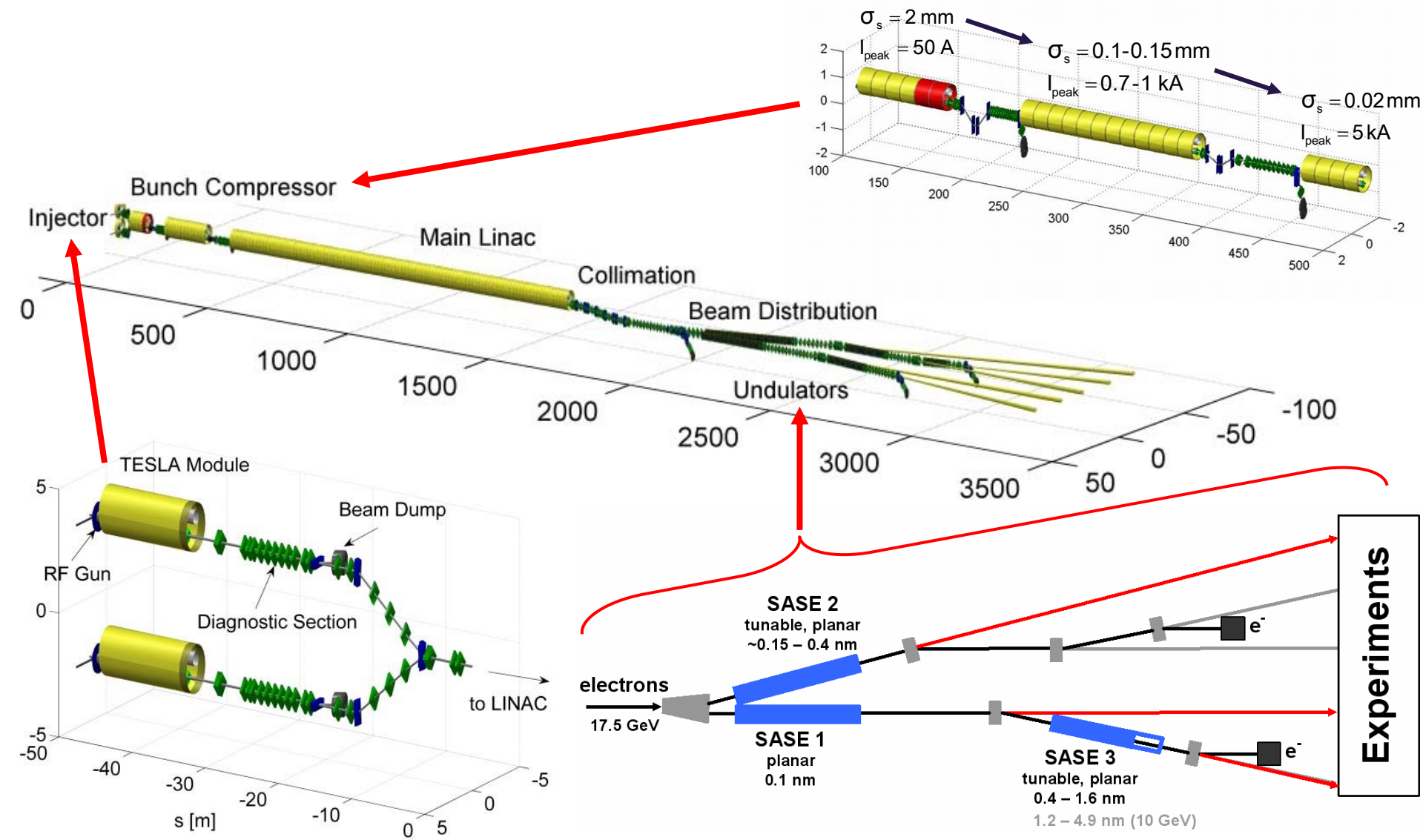
- Free-electron LASer in Hamburg (FLASH)
- European X-ray Free-Electron Laser (European XFEL)



Free electron LASer in Hamburg (FLASH): first lasing 4.12 nm in Nov. 2010



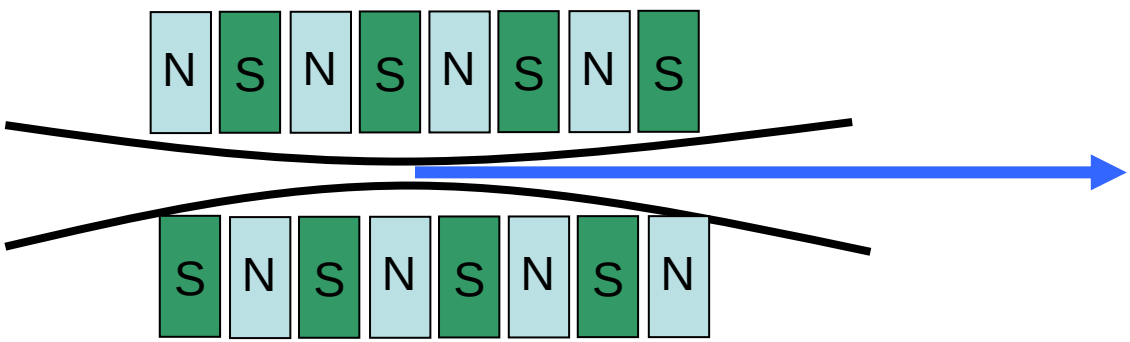
European X-ray Free Electron Laser (European XFEL): ~0.1 nm lasing

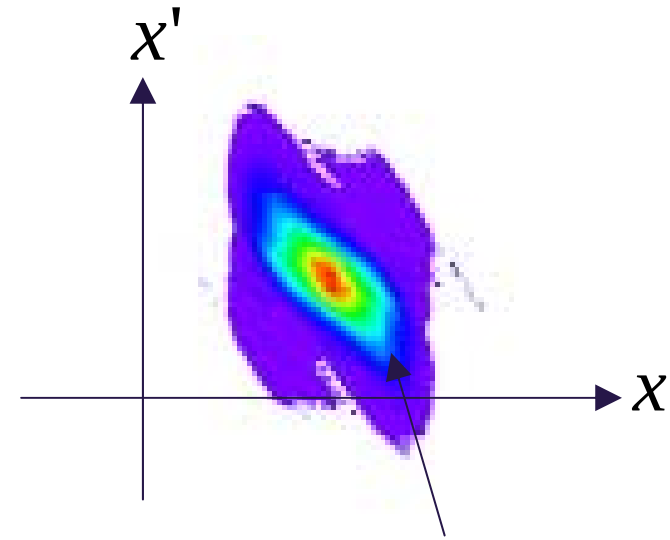


(start-up version)

Quality of Electron Beams and Lights for FELs: Brightness & Emittance

FELs require the electrons to be focused into the optical beam over the undulator length





differential intensity at a given point on "phase space" distribution gives $dI / dxdx'$

Beam brightness is a local property that measures the achievable current density for a given angular acceptance

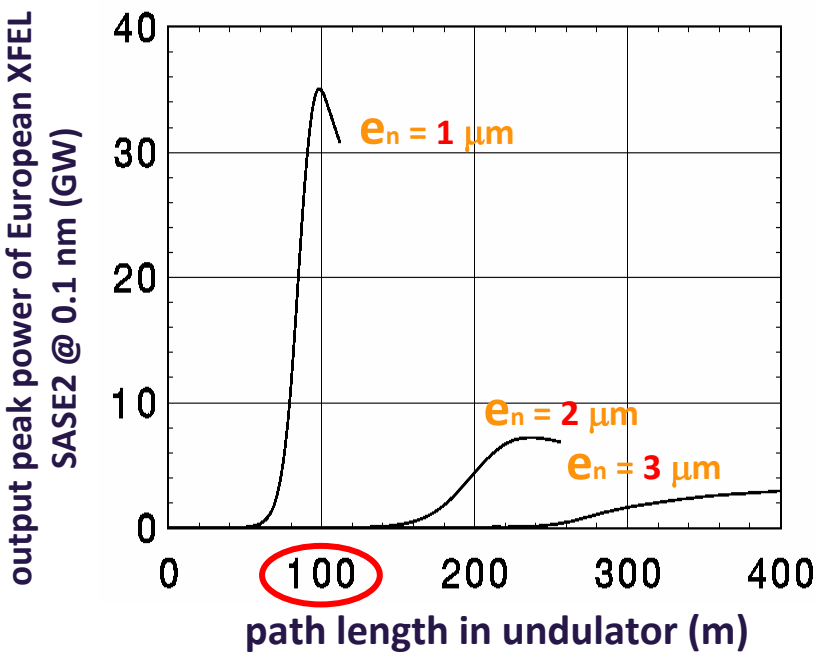
$$B = \frac{d^2 I}{dA d\Omega} = \frac{d^2 I}{dx dx' dy dy'} \propto \frac{2 I_p}{\varepsilon_x \varepsilon_y}$$

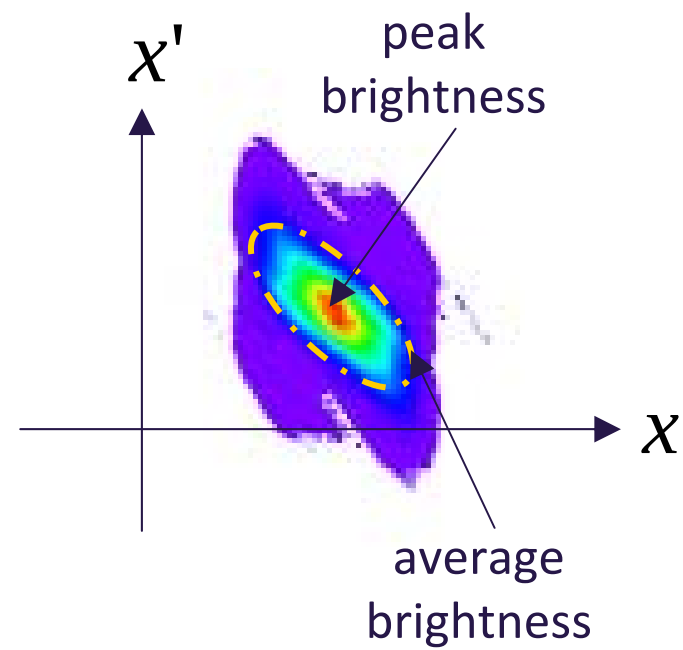
I **- electron beam current**
A **- transverse area**
Ω **- the divergence**
x, y **- coordinates transverse to the beam motion (along *z*)**
x', y' **- indicate derivatives with respect to *z***

Area in phase space
↓
Emittance (ε) of the beam

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

Electron Beam Quality for FEL: Brightness & Emittance





To achieve European XFEL brightness (B) for 0.1 nm lasing

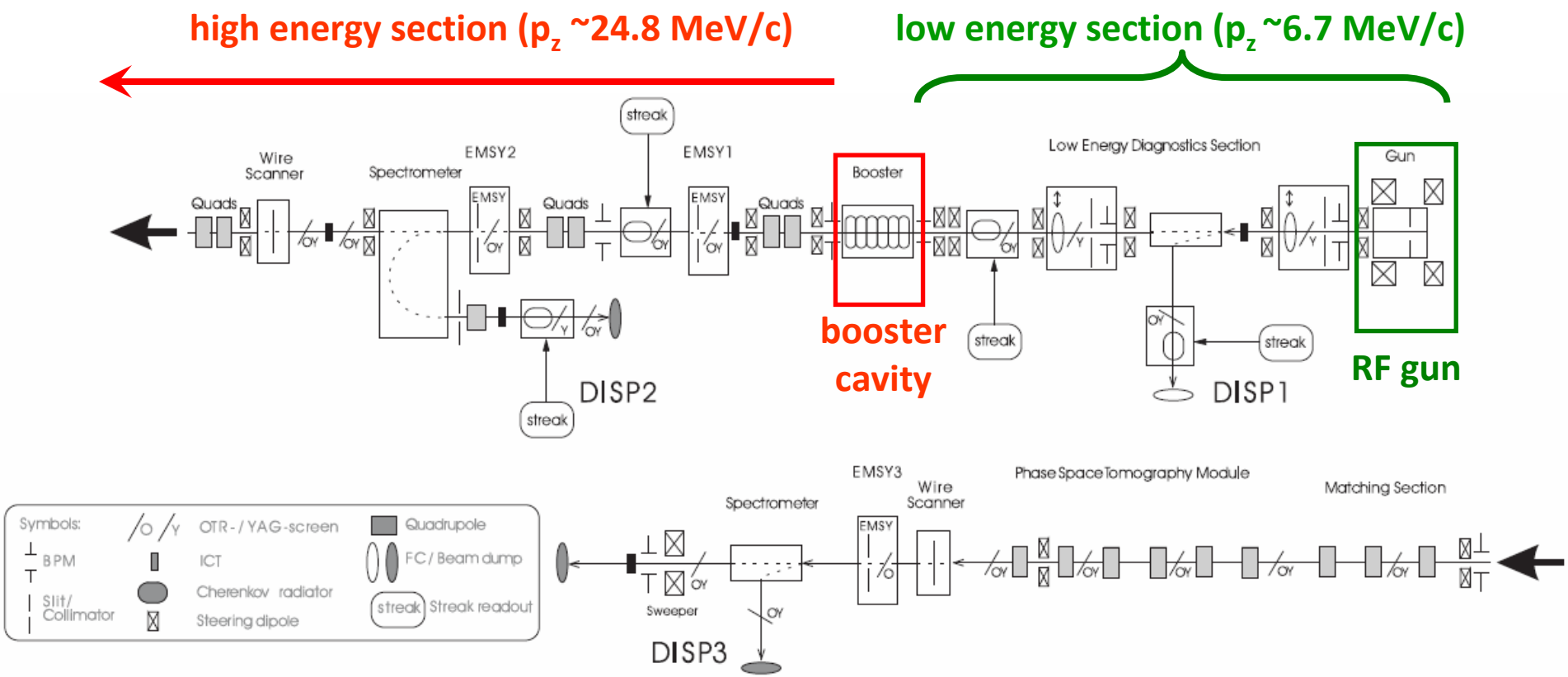
- Peak current (I_p): 5 kA, energy spread: 2.5 MeV
  → can be improved e.g. bunch compressor
- Transverse slice emittance @ undulator entrance: 1.4 mm-mrad
- Nominal projected emit. @ injector exit: **0.9 mm-mrad** for 1 nC
  → injector's property (much be small from the source)

$$B \propto \frac{2I_p}{\varepsilon_x \varepsilon_y}$$

Goals & research activities @ PITZ

- Development & optimization of electron sources for the European XFEL
  - small transverse emittance (≤0.9 mm-mrad @ 1 nC)
  - stable production of short bunches with small momentum spread
  - operation with high duty cycle (for superconducting cavity linac)
    - long RF pulse length of 650 μs @ 10 Hz repetition rate
    - electron pulse train operation of 4.5 MHz
- Preparation (conditioning) & characterization of RF guns for subsequent operation at FLASH & European XFEL
- Extensive R&D on photo injectors in parallel to FLASH operation
  - benchmark for theoretical & experimental understanding of photo injectors
  - test new developments e.g. laser system, cathodes, beam diagnostics

Current PITZ Setup



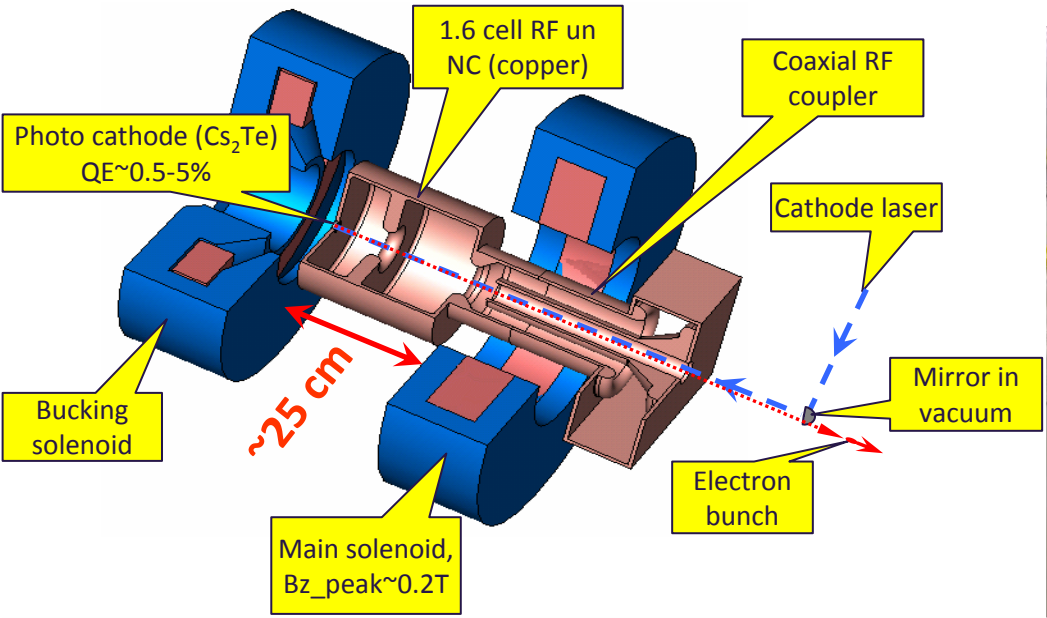
Bunch charge is measured with

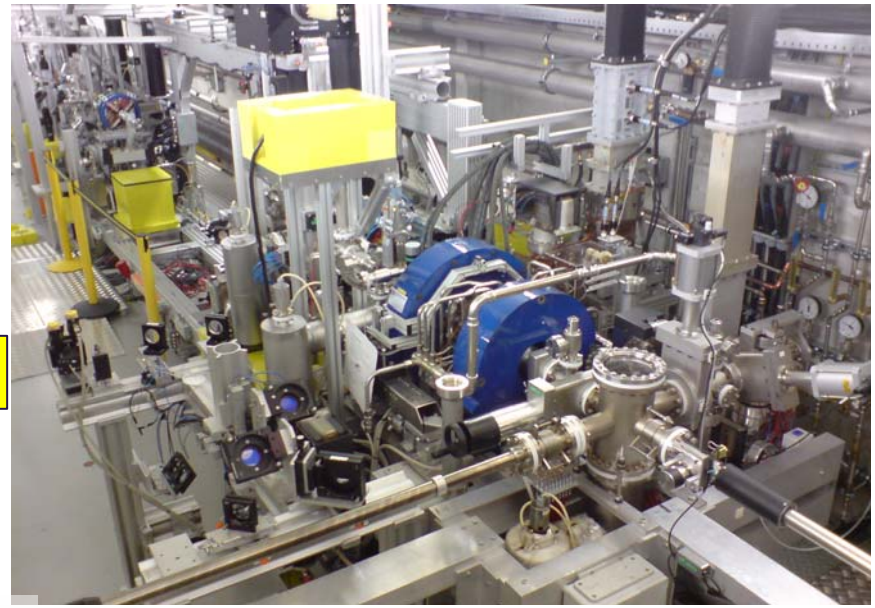
- Faraday cup (FC)
- Integrating current transformer (ICT)

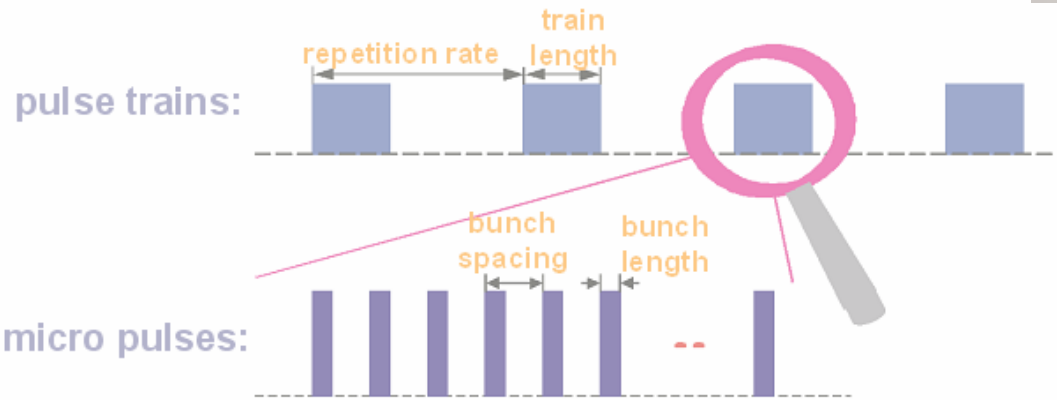
Beam size and beam profile are measured with

- observation screens:
  - **Ce-doped Yttrium Aluminum Garnet (YAG) powder coating screen**
  - **Optical Transition Radiation (OTR) screen**
- beam position monitor (BPM)
- wire scanners

Characterization of L- band Photo Cathode RF guns (6 guns since 2001)





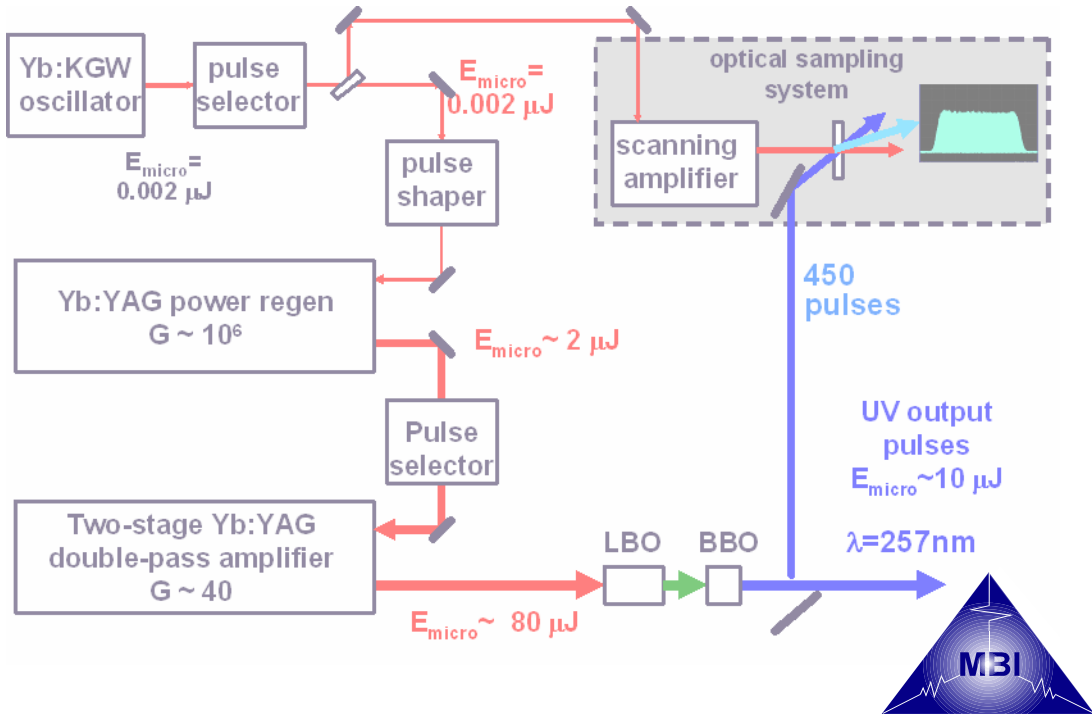


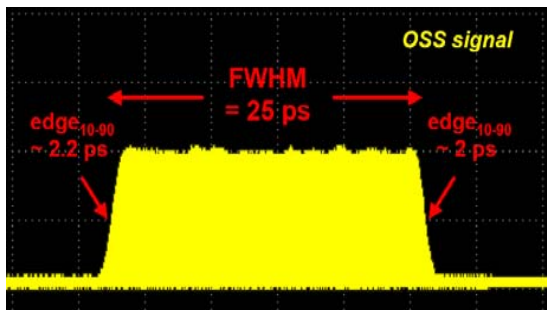
Parameter	Value
Max. RF repetition rate	10 Hz
Max. RF power	6 MW peak power
Max. RF pulse length	800 μs
Max. RF average power	50 kW (in 25 cm cavity)
Bunch spacing	0.2 – 1 μs (for XFEL)
Max. momentum	6.7 MeV/c
Max. bunch charge	a few nC

Accelerator is a space-charge dominated regime!
(further acceleration is needed)

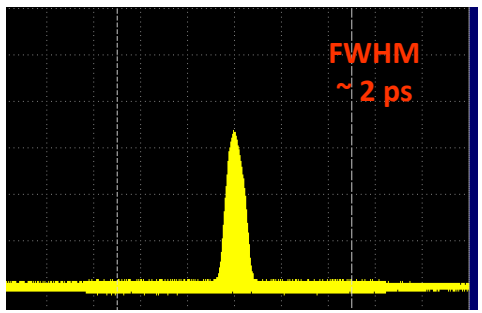
Photo Cathode Laser System

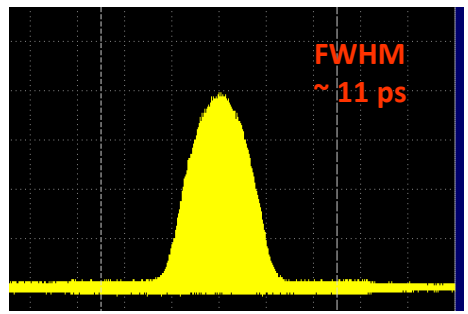
- Ytterbium-doped YAG laser (Yb:YAG)
  - IR input pulses
- UV output pulses
  - λ = 257 nm
  - pulse repetition rate = 1 MHz
  - micro bunch energy: up to 10 µJ
- Adjusting of pulse shape is the main important parameter of laser system @ PITZ
  - can generate a broad variety pulse shapes of flat-top and Gaussian





Flat-top pulses of different durations and rise/fall time (max. flat-top ~25 ps FWHM)



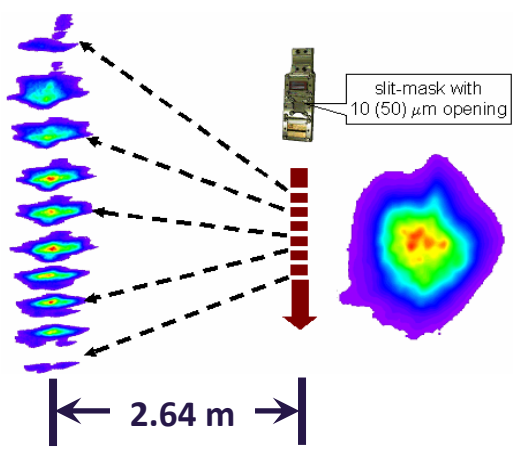


Gaussian pulses of different durations (FWHM = 2 -14 ps)

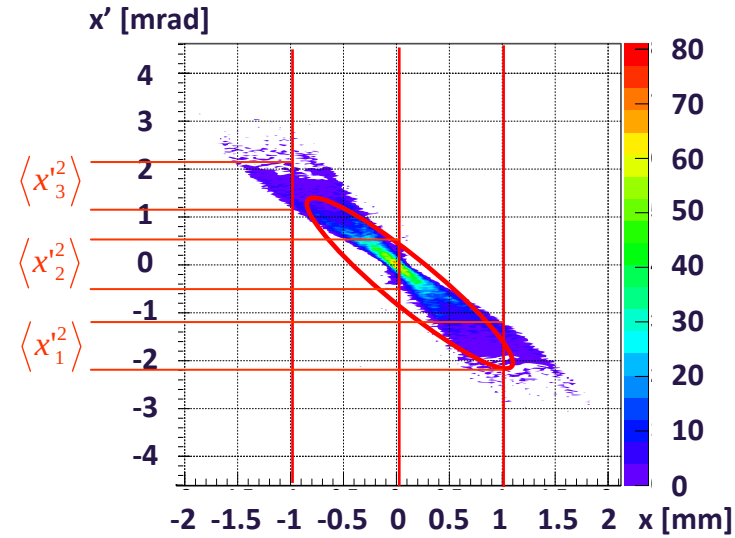
Measurement of Transverse Projected Emittance and Phase Space

Single slit scan technique

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



Observation screen **EMSY1 (z = 5.74 m)**



2D scaled normalized RMS emittance

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

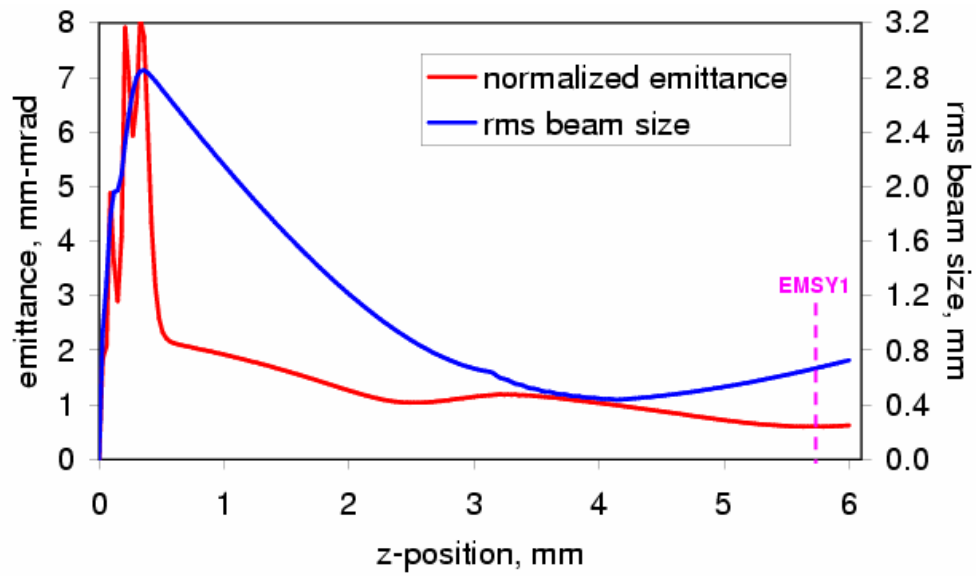
$\langle x^2 \rangle$, $\langle x'^2 \rangle$ - second central moments of electron distribution and divergence in phase space

$x' = p_x/p_z$ - angle of the single electron trajectory

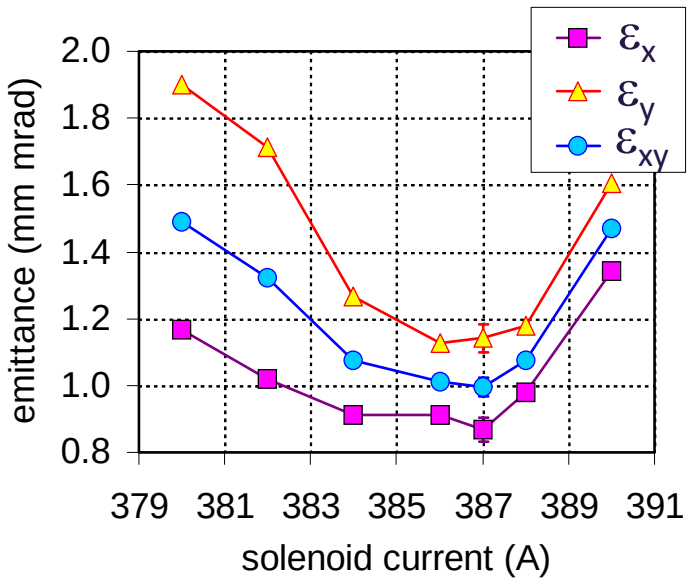
σ_x - RMS beam size measured at slit location

Measurement of Transverse Projected Emittance and Phase Space

Dependence of emittance and RMS beam size on longitudinal position along the beam line



Measured horizontal (ε_x), vertical (ε_y) and geometrical emittance vs. solenoid current



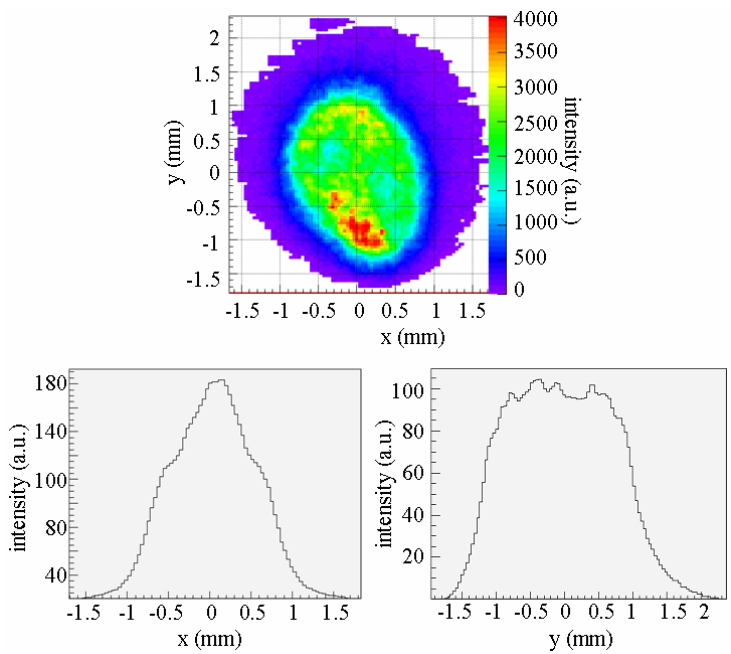
Machine & beam parameters

- gun phase: +6 deg from MMMG phase
- booster phase: MMMG phase
- beam energy: 14.7 MeV/c
- flat-top laser profile: 2.1/23.1\2.4 ps
- laser (RMS) spot size: 0.36 mm

geometrical emittance: $\varepsilon_{xy} = \sqrt{\varepsilon_x \varepsilon_y}$

Measured Results of Transverse Projected Emittance and Phase Space for 1 nC

Measured beam distributions and profiles



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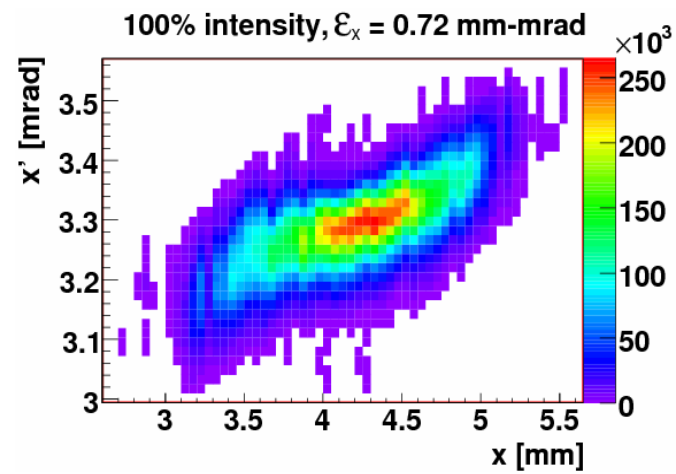
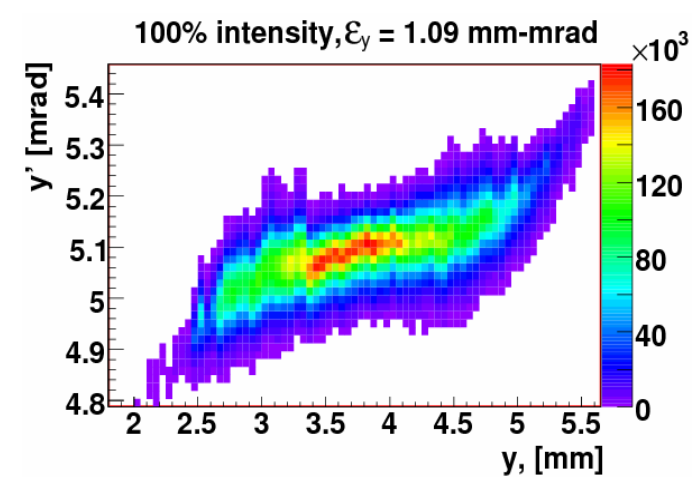
- flat-top laser profile: 2.1/23.1\2.4 ps
- laser (RMS) spot size: 0.36 mm

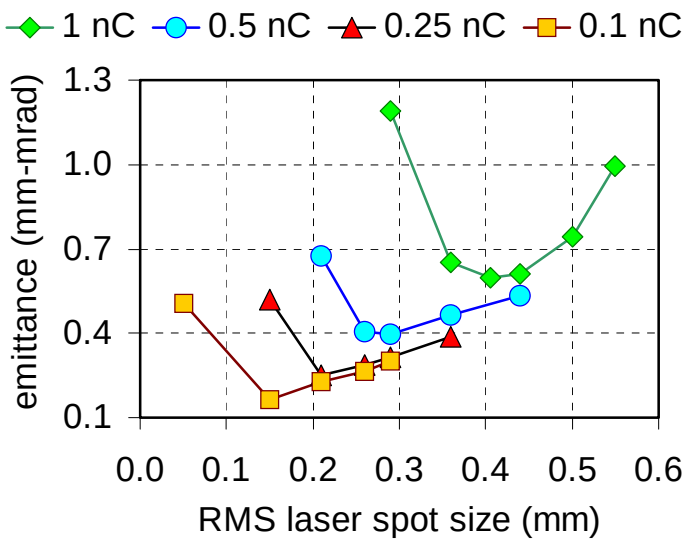
Measured horizontal (ε_x) and vertical (ε_y) phase space distributions for minimum emittance point of 1 nC bunch charge





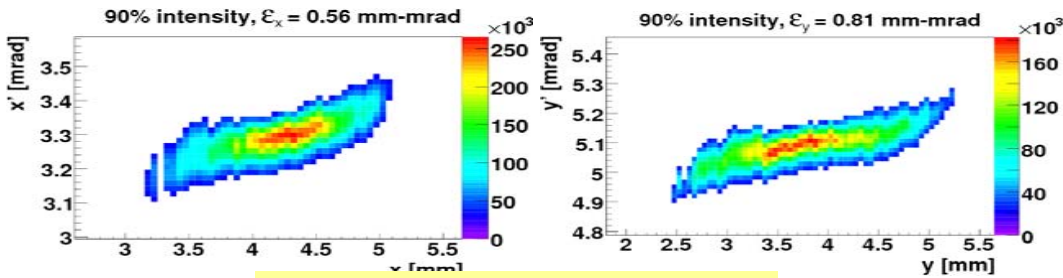
Measurements of Transverse Projected Emittance for Different Bunch Charges

Measured normalized geometric mean emittance (ε_{xy}) vs. RMS laser spot size

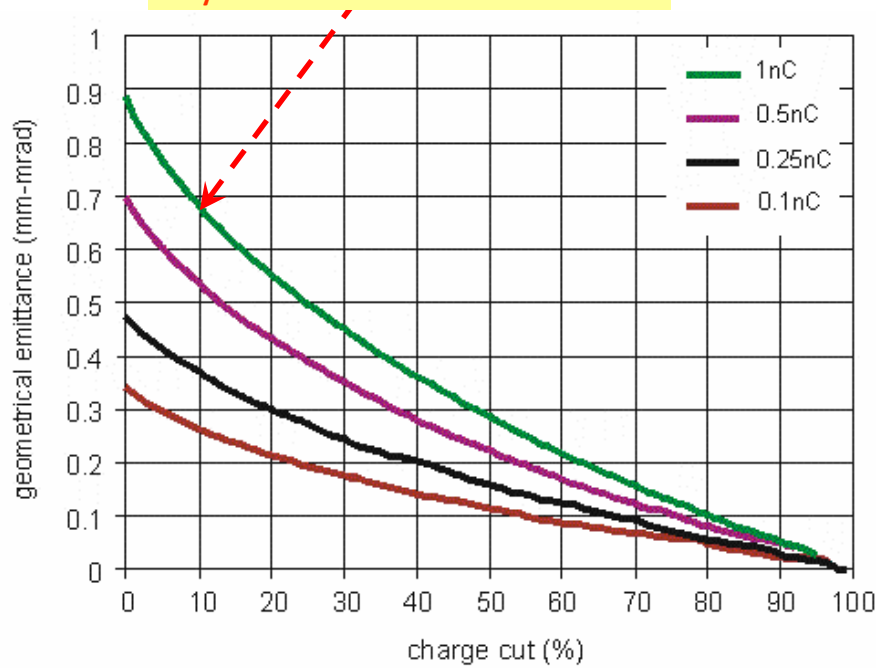


Q (nC)	1	0.5	0.25	0.1
ε_x	0.72±0.01	0.53	0.42	0.29
ε_y	1.09±0.02	0.77	**0.53**	0.37
ε_{xy}	**0.89±0.01**	0.64	0.47	0.33

Core emittance values - removing 10% of bunch charge from the low intensity tails of phase space distribution, which probably do not contribute to FEL lasing process

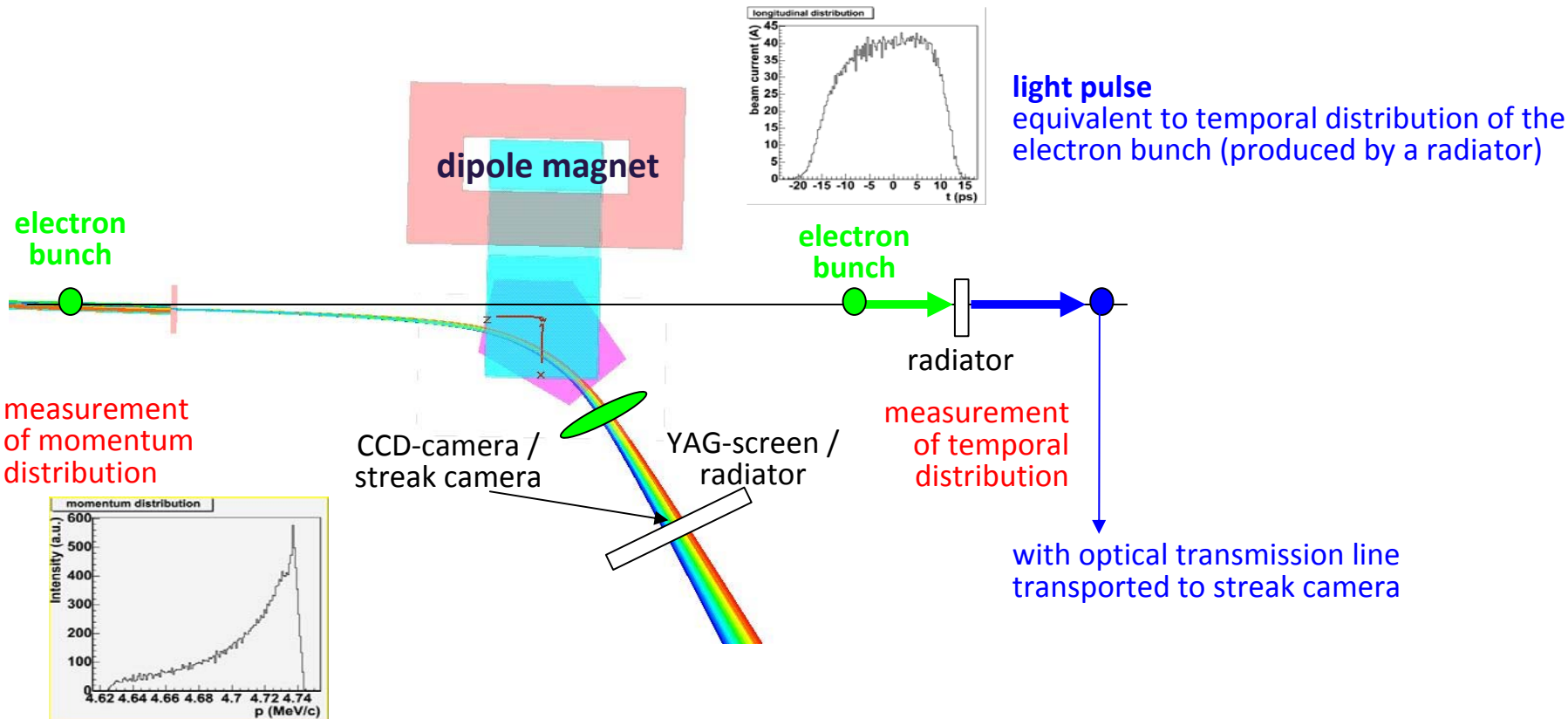


ε_{xy} = 0.67 mm-mrad @ 1 nC



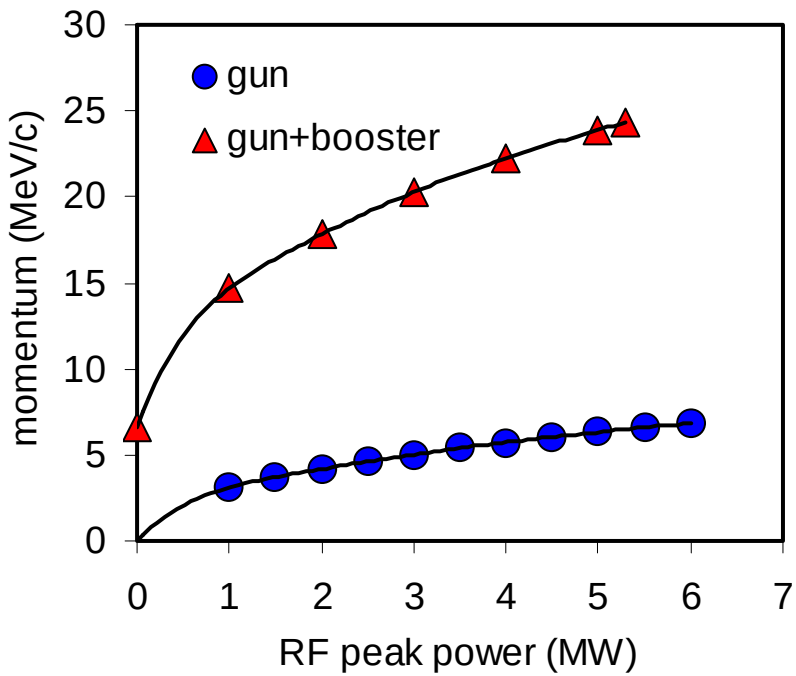
Measurement of Momentum & Longitudinal Phase Space

- Beam momentum and momentum spread
  - → deflects the beam using dipole magnet (beam momentum vs. dipole magnetic field)
  - → measures electron distribution @ observation screen (reconstruct moment spectrum)
- Bunch length and longitudinal distributions
  - → generates Cherenkov radiation @ aerogel screen
  - → measured bunch length using streak camera



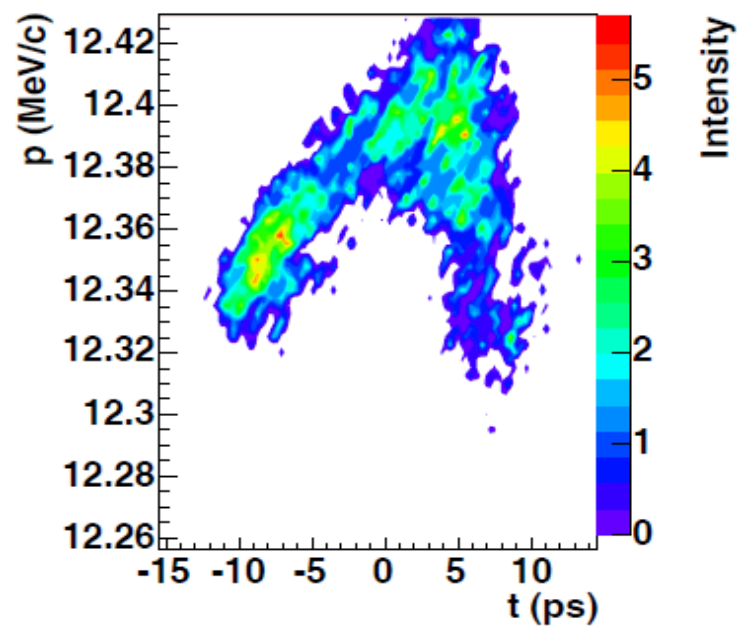
Measured Momentum & Longitudinal Phase Space

Measured momentum of the electron beam as a function of the RF peak power



- gun gradient: 60 MV/m at the cathode
- gun & booster phase: maximum mean momentum gain (MMMG) phase

Example of measured longitudinal phase space distribution for electron beam with mean momentum of 12.4 MeV/c



- gun gradient: 60 MV/m at the cathode
- gun phase: MMMG phase
- booster phase: -10° from MMMG phase

Summary

- Research activities at PITZ are ongoing to develop and optimize electron beams for FLASH and European XFEL
- Measurement results demonstrated beam parameters for the European XFEL photo injector
  - Operation of RF gun with gradient of 60 MV/m
  - RF average power in the gun ≥50 kW
  - Normalized transverse projected emittance ≤ 0.9 mm-mrad
- Upgrades of the PITZ facility to extend ability for beam diagnostics were done and will be continued

Measurement of Transverse Slice Emittance

Measure transverse emittance at different longitudinal position along the bunch

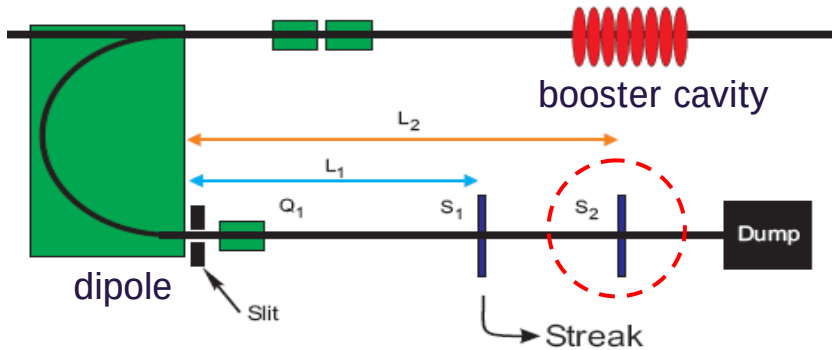
→ need linear correlation between particle's momentum and its longitudinal position

→ operate booster off-crest from the max. acceleration phase (low momentum, large momentum spread)

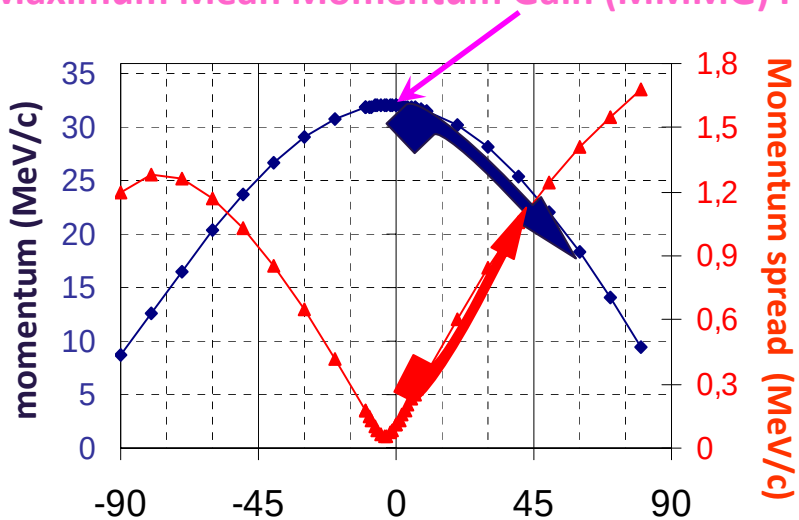
→ measure emittance in transverse direction orthogonal to the dipole deflecting plane

Measurements in 2nd dispersive section

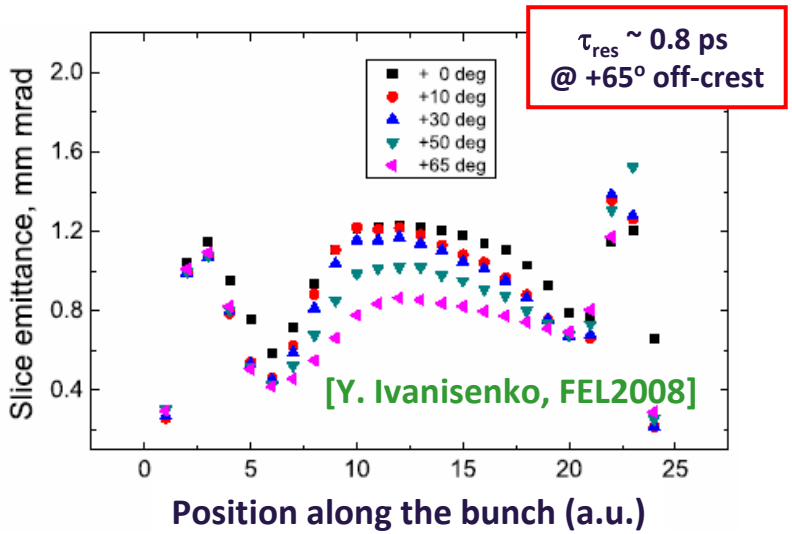
→ horizontal slice emittance



Maximum Mean Momentum Gain (MMMG) Phase



booster phase from MMMG phase (degree)



Simulated slice emittance of the beams accelerated with different phases off-crest