Photo Injector Test facility at DESY, Zeuthen site.

PITZ: facility overview

Mikhail Krasilnikov (DESY) for the PITZ Team
Mini-workshop on THz option at PITZ, Zeuthen, 22.09.2015

HELMHOLTZ
ASSOCIATION

DESY

Photo Injector Test facility at DESY, Zeuthen site

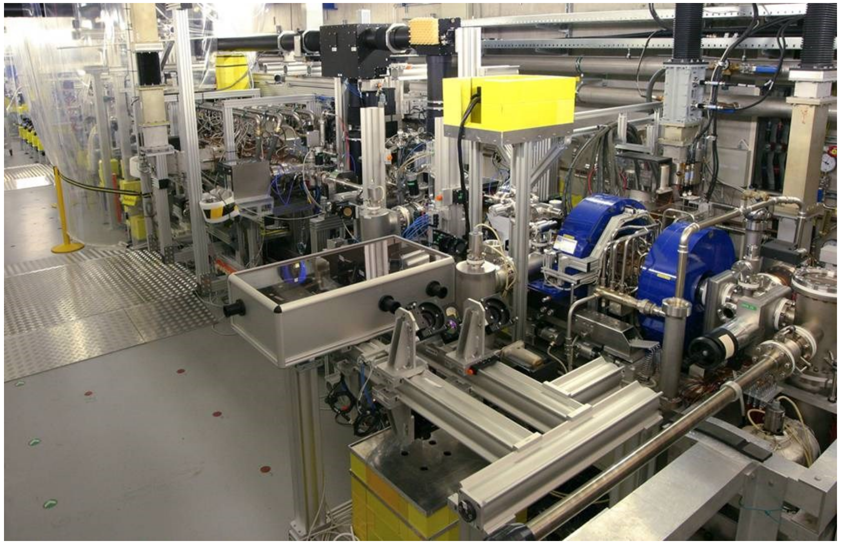
The Photo Injector Test facility at DESY in Zeuthen (PITZ) focuses on the development, test and optimization of high brightness electron sources for superconducting linac driven FELs:
⇒ test-bed for FEL injectors: FLASH, the European XFEL (conditioning and characterization of gun cavities and photo injector subsystems, e.g. photocathode laser)

⇒ **High brightness → small ε_{tr}** (projected and slice)

⇒further studies → e.g. cathodes: dark current, photoemission, QE, thermal emittance, …
+ **detailed comparison with simulations = benchmarking for the PI physics**

Highest priority at PITZ currently:

Participate in the solution of the remaining problems of the RF gun for XFEL (RF windows, cathode RF contact spring, stability and long term reliability)

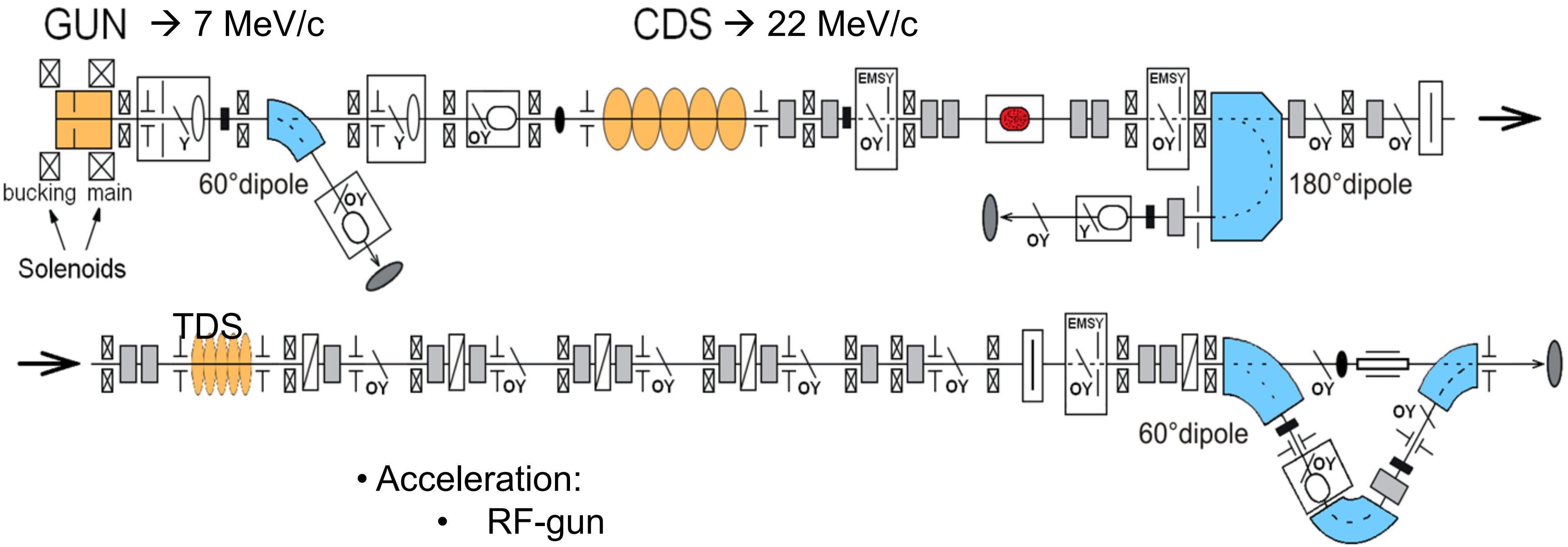


High Brightness Photo Injector for XFEL

parameter	XFEL injector, nominal	XFEL, commissioning	PITZ, 2015	Remark
RF gun gradient (peak power)	E_{cath}=60MV/m (6.5MW)	E_{cath}=50…53MV/m (4.5…5.0MW)	E_{cath}=53MV/m (5MW)	
RF pulse length	650us	650us	650us	Priority w.r.t. the peak power
Repetition rate	10Hz	10Hz	10Hz	
RF gun phase stability (rms)	0.01deg		0.07deg	
RF gun amplitude stability (rms)	0.01%		0.02%	
Cathode laser (FWHM)	Flattop (2/20\2ps)	Gaussian (~13ps FWHM)	Gaussian (~11-12ps FWHM)	Pulse shaper issue
Bunch charge Beam emittance	0.02 – 1 nC 0.4 – 1 mm mrad	0.1 – 1 nC e.g. ≤ 1 mm mrad @500pC	0.1 – 1 nC 0.8 mm mrad	E_{cath}=53MV/m, Gaussian laser pulse

Required electron beam quality demonstrated at PITZ in 2011 with ≤200us RF pulse length

PITZ layout

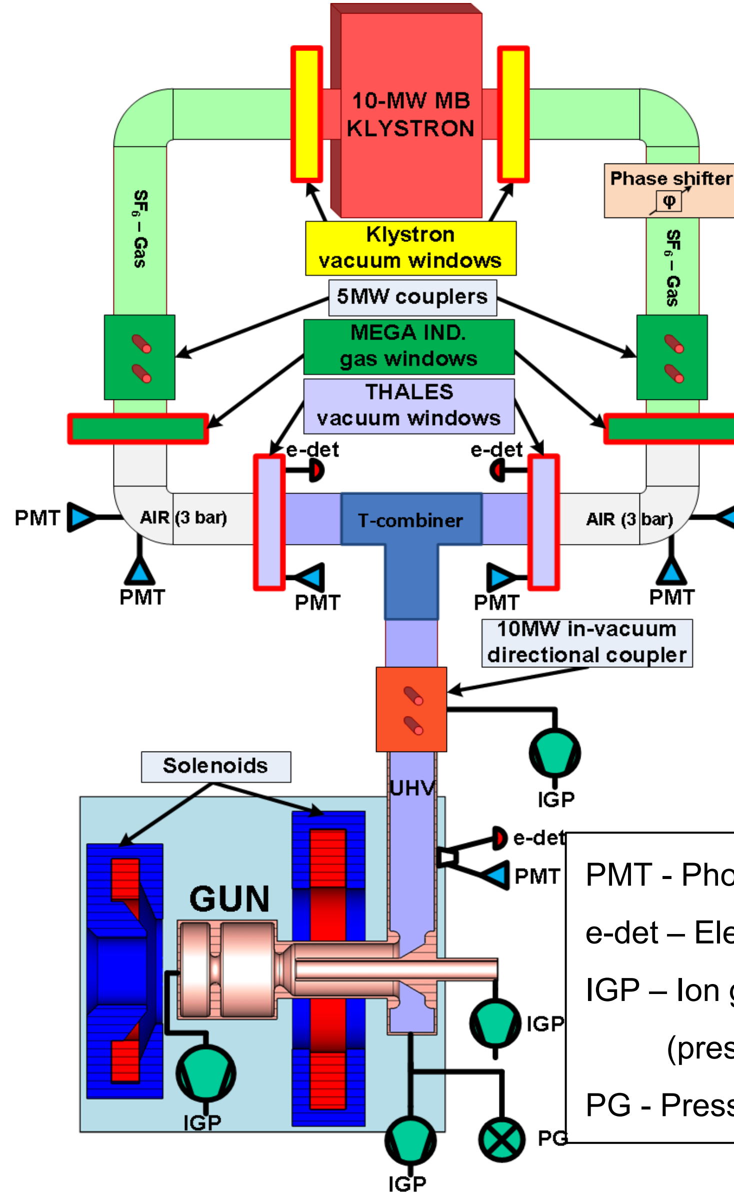


- Acceleration:
  - RF-gun
  - Booster
- Magnets:
  - Main and bucking solenoids
  - Dipoles
  - Steerers
  - Quadrupoles
- Other components:
  - Diagnostics
  - Plasma cell → PDWA
  - Auxiliary (e.g. BLM)

Current PITZ RF-Gun Setup

Now: **2 Thales RF window solution** is under test at PITZ:

- Peak RF power in gun ~6.5MW
- RF pulse length ~650 us
- Repetition rate 10Hz
- Goal: <1 gun IL(trip) / week



RF vacuum windows position:

- adapted to available RF components
- compatible with XFEL setup

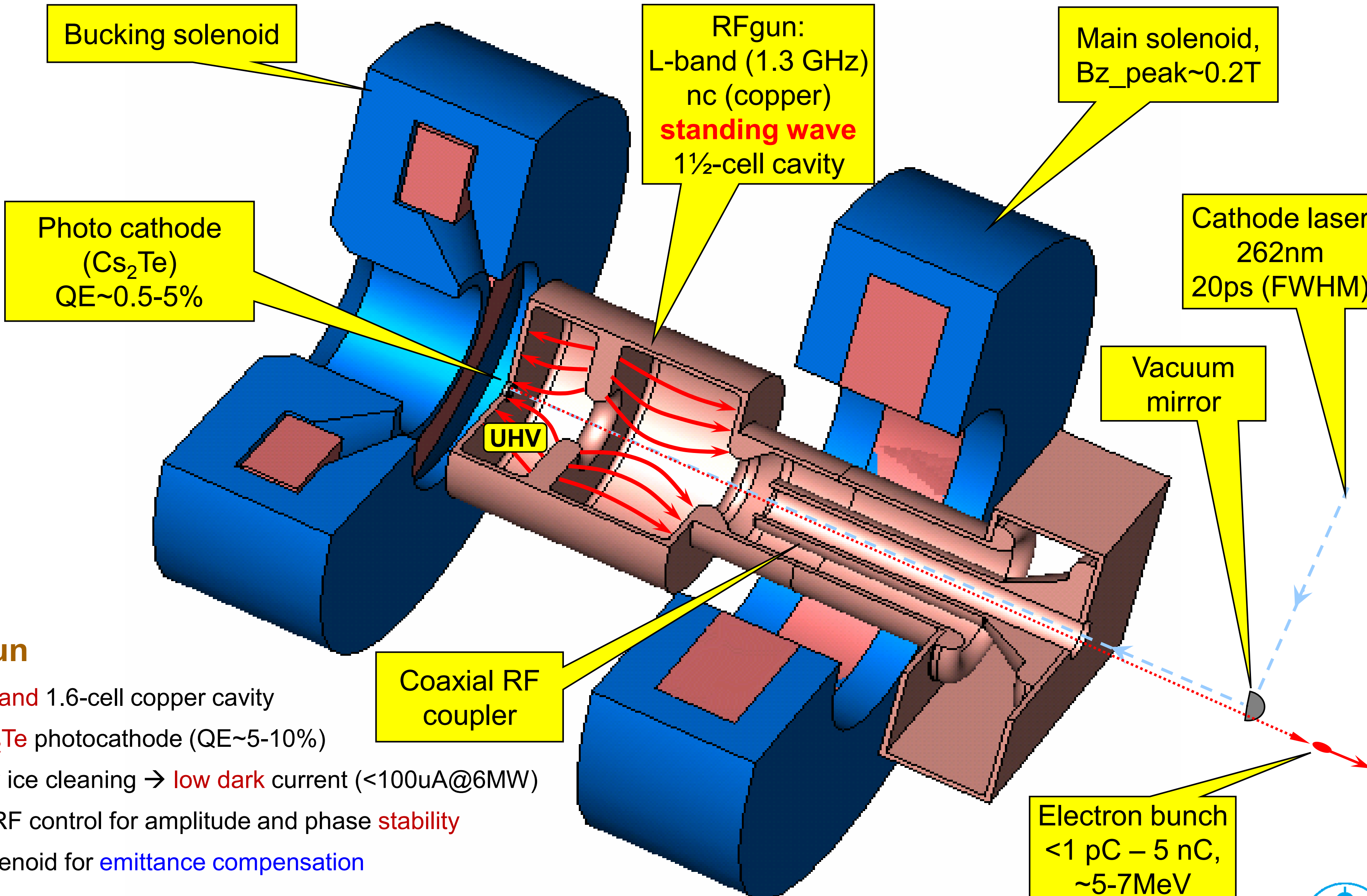
PMT - Photomultiplier tube

e-det – Electron detector

IGP – Ion getter pump (pressure reading)

PG - Pressure gauge

Photo Injector: RF-Gun



RF gun

- L-band 1.6-cell copper cavity
- Cs_2Te photocathode (QE~5-10%)
- Dry ice cleaning → low dark current (<100uA@6MW)
- LLRF control for amplitude and phase stability
- Solenoid for emittance compensation

PITZ Photocathode laser (Max-Born-Institute, Berlin)

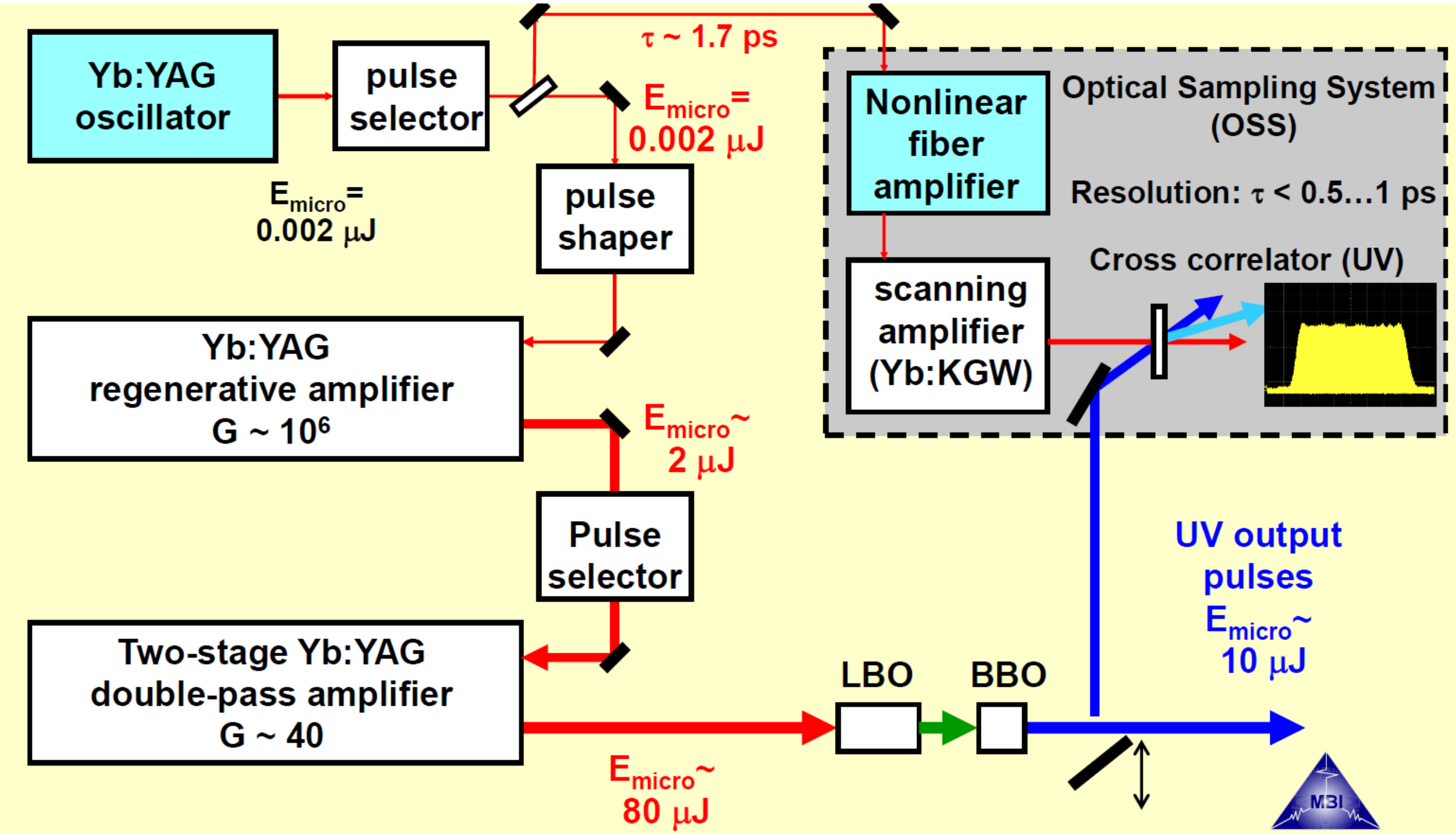
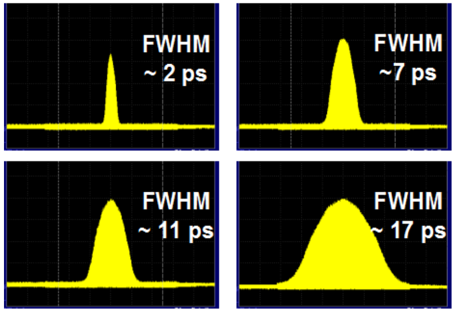
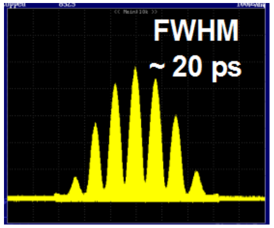


Photo cathode laser: temporal pulse shaping

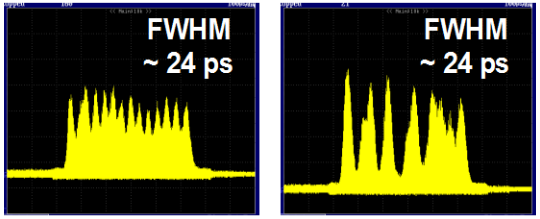
Multicrystal birefringent pulse shaper containing 13 crystals

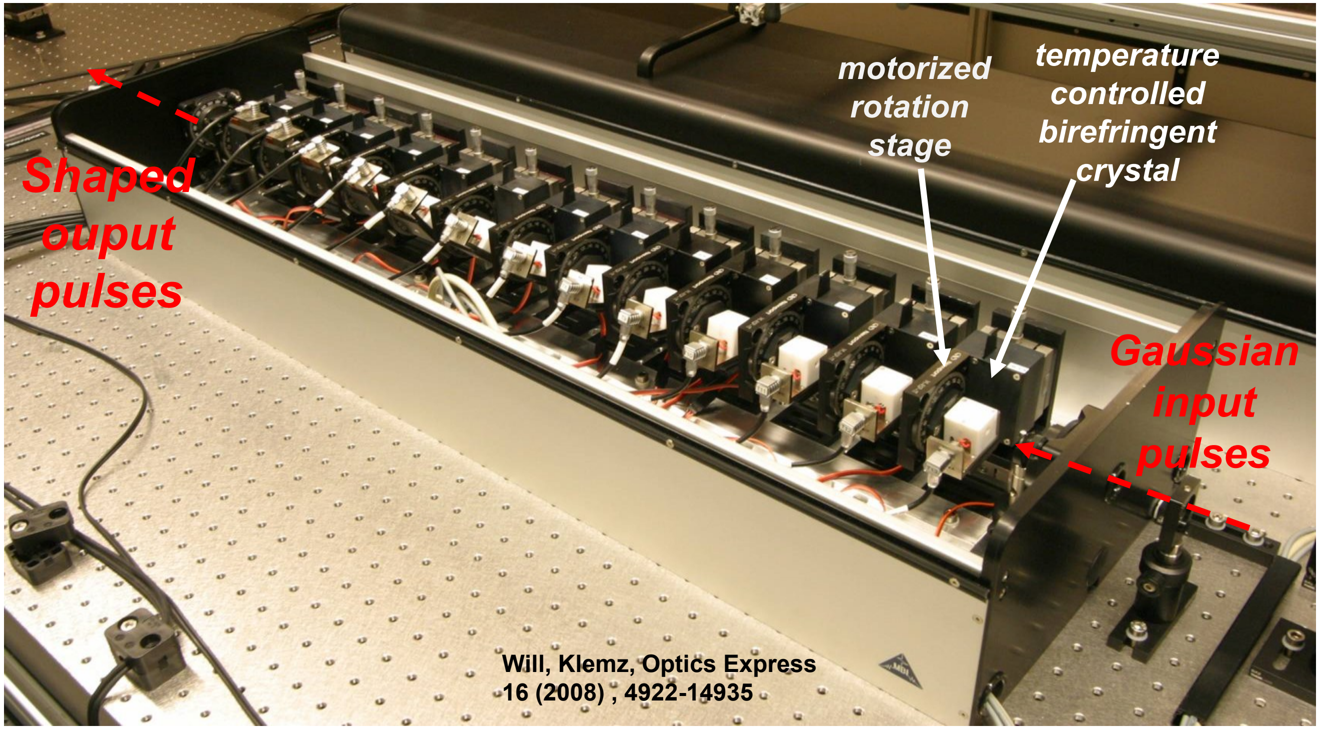
Gaussian:

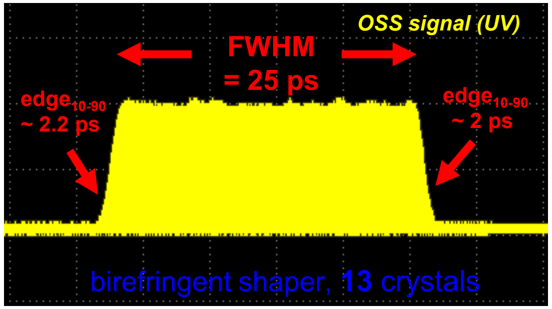




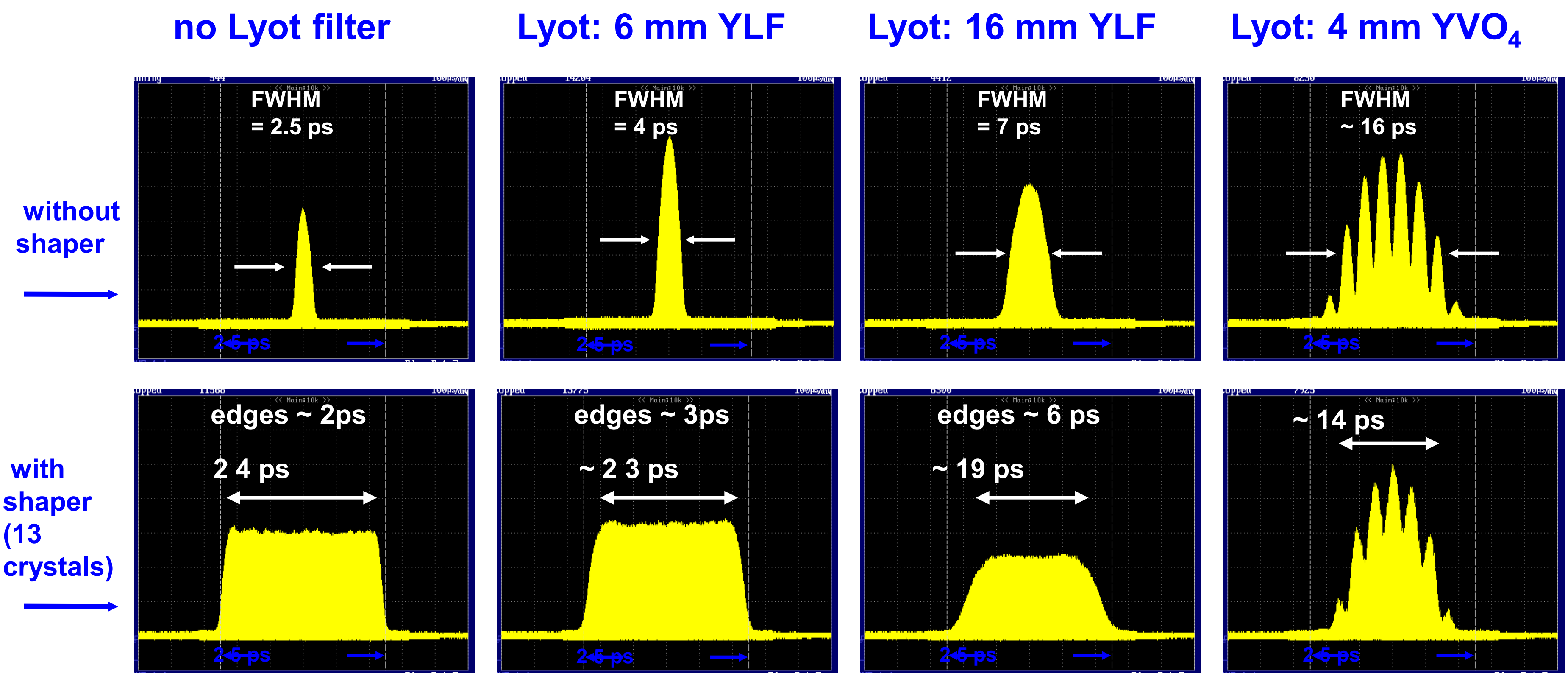
Simulated pulse-stacker







Variation of the pulse shape by using a single different Lyot filter (UV, measured with OSS)



- Edges of the flat-top pulses are slightly shorter than FWHM of the Gaussian pulse (measured without shaper)
- **“Smoothening” of the Modulations** in the flat-top region of the pulse

I. Will, G. Klemz „Increasing the flexibility in pulse shape of a Yb:YAG photocathode laser” 20.06.2009

Laser temporal profile for high TR PWA experiment

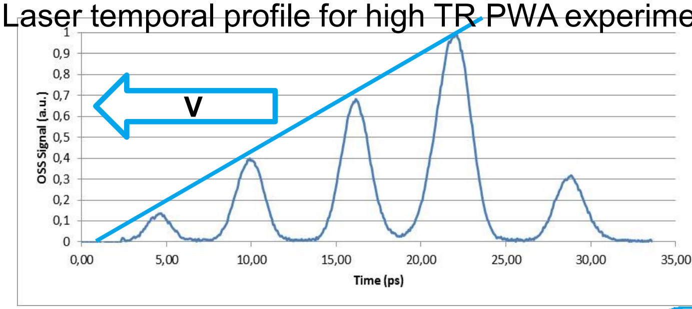
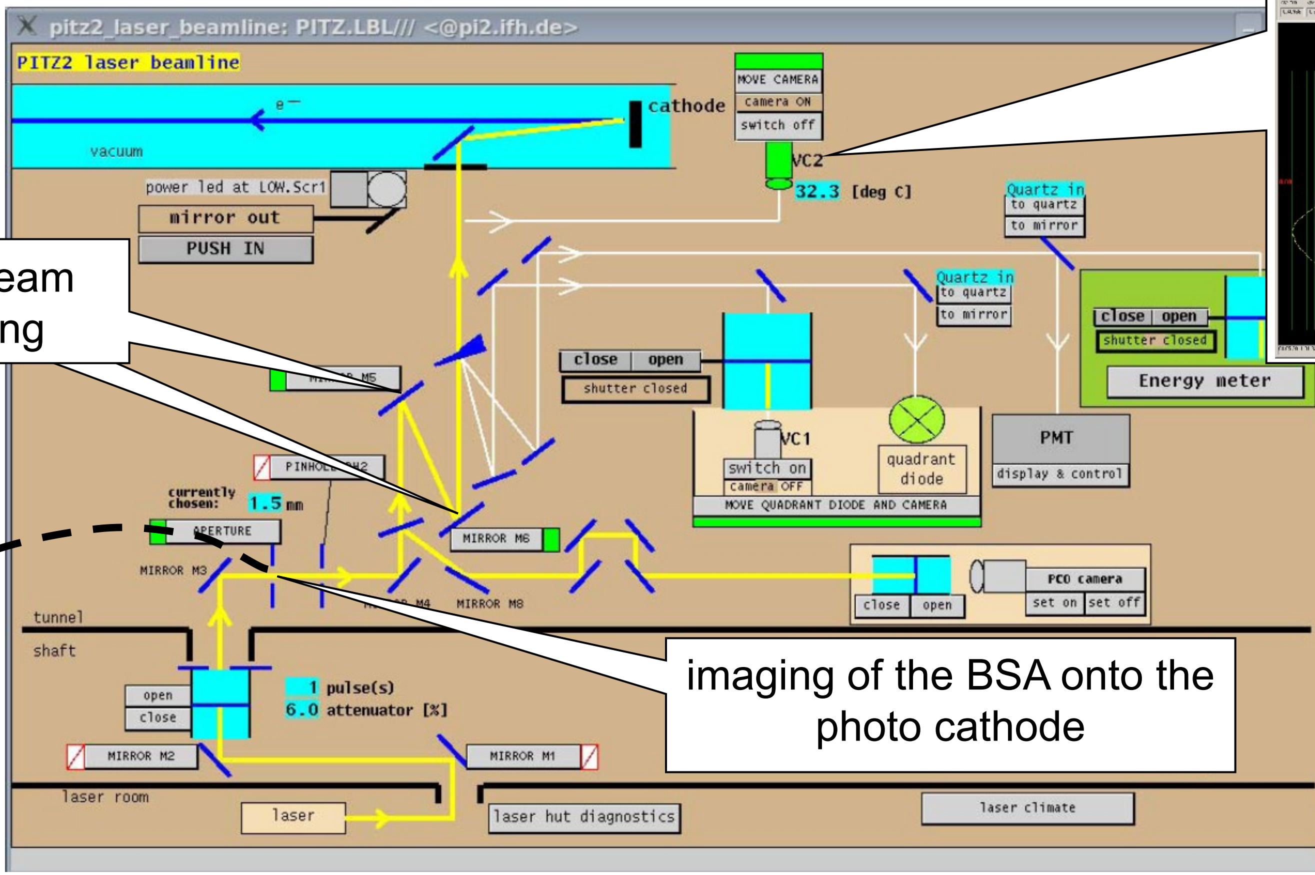
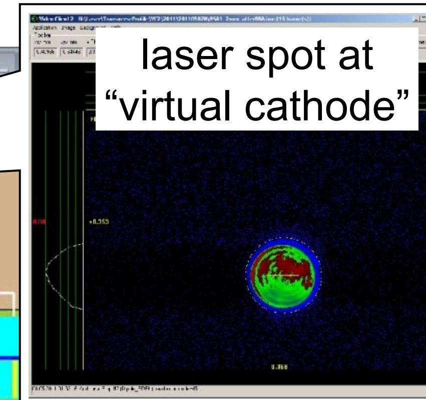


Photo cathode laser: transverse pulse shaping

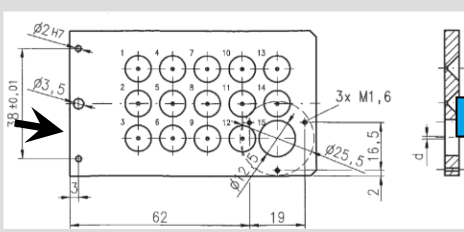


laser beam steering

imaging of the BSA onto the photo cathode

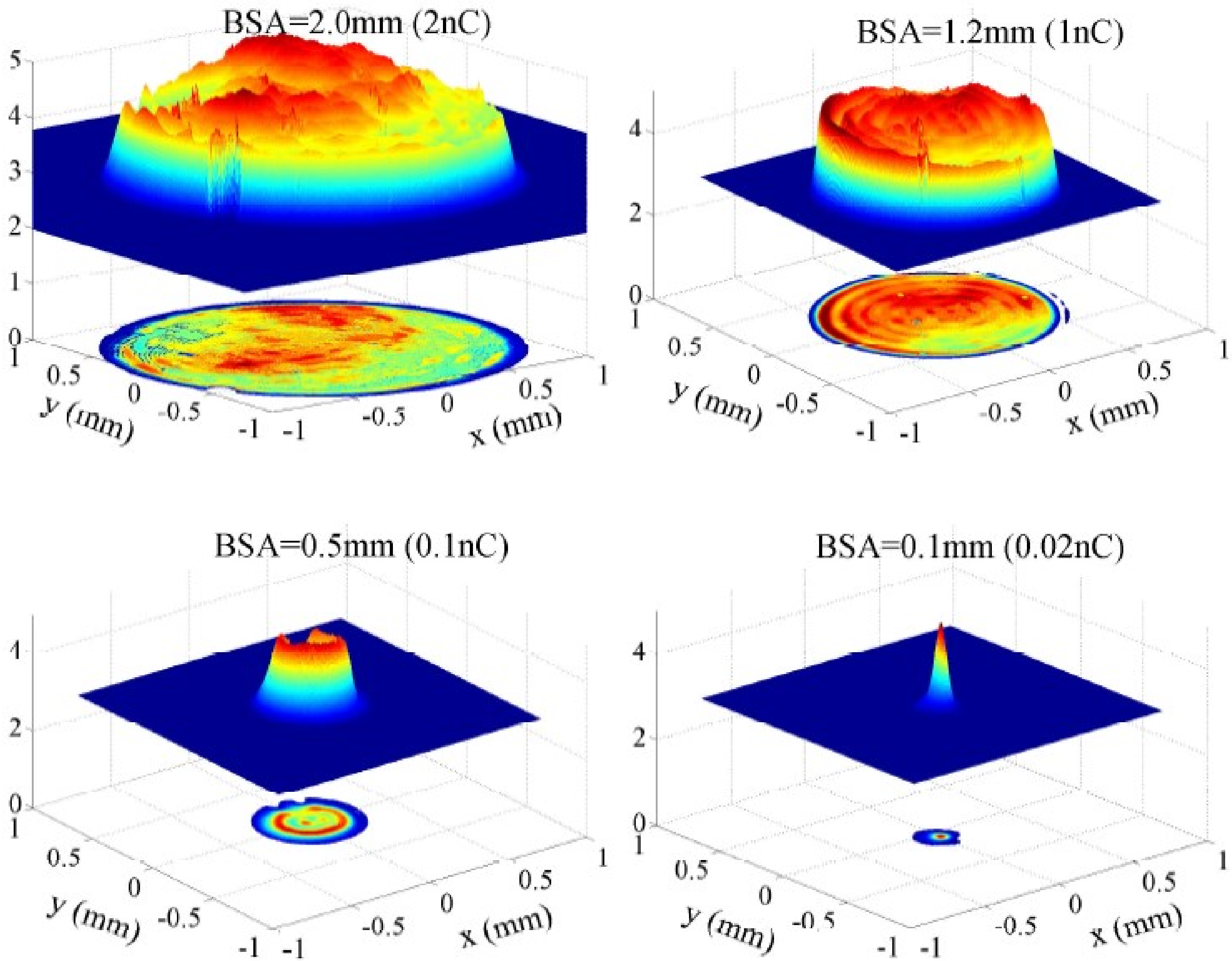


laser spot at “virtual cathode”



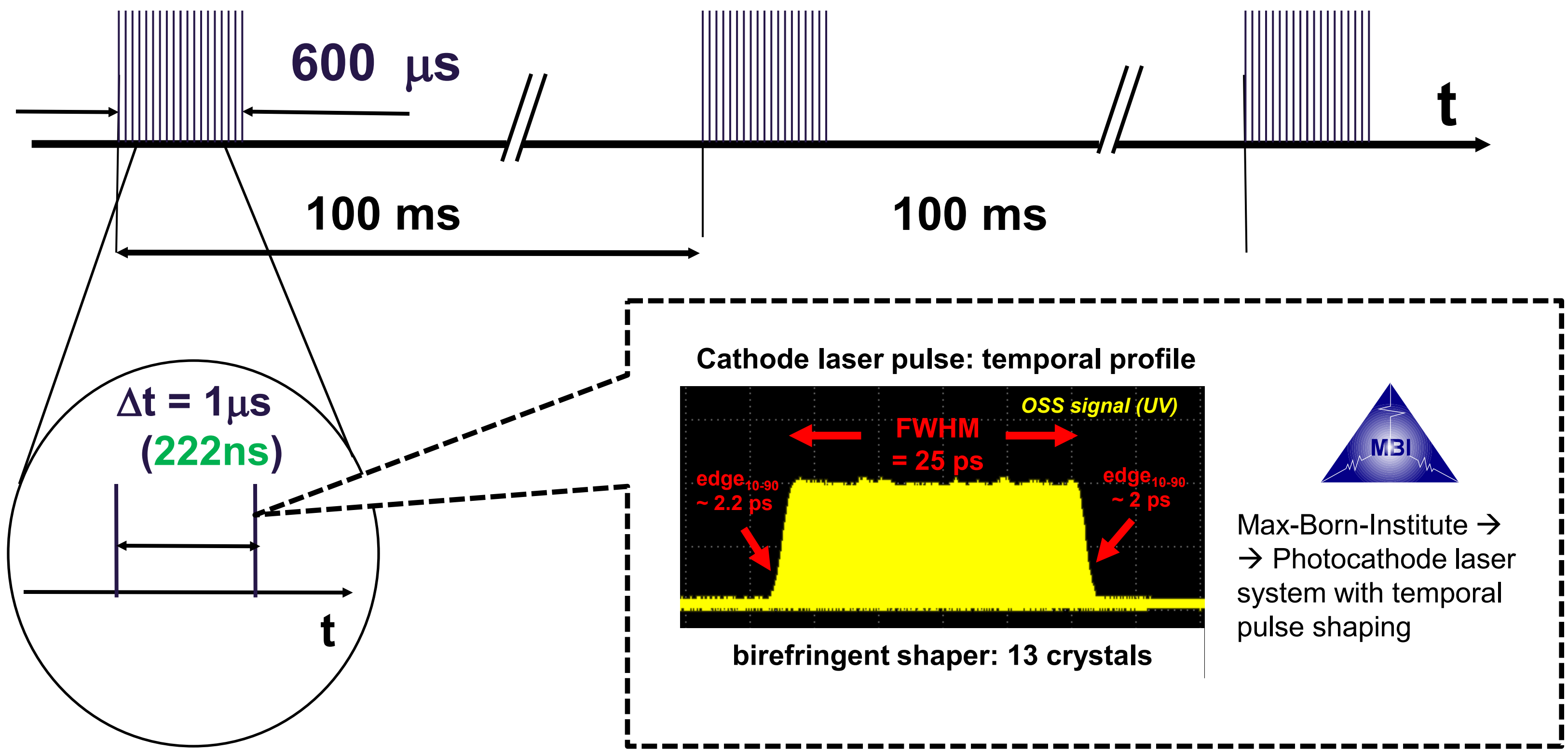
Beam Shaping Aperture (BSA) plate is now replaced by an iris with remotely tunable opening

Photo cathode laser: transverse distributions



Pulse Train Time Structure: PITZ and European XFEL

Trains with up to 600 (2700) laser pulses ➔ electron bunches of 1nC each

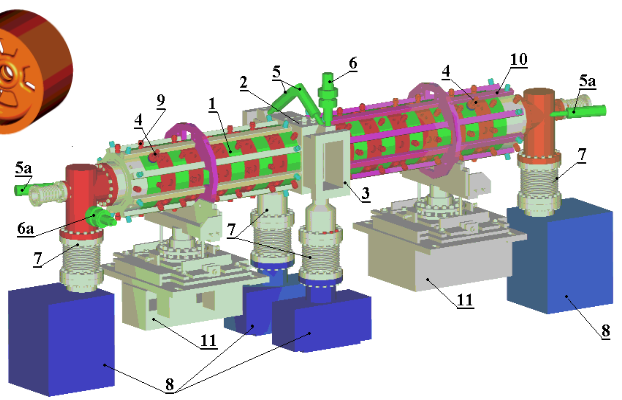


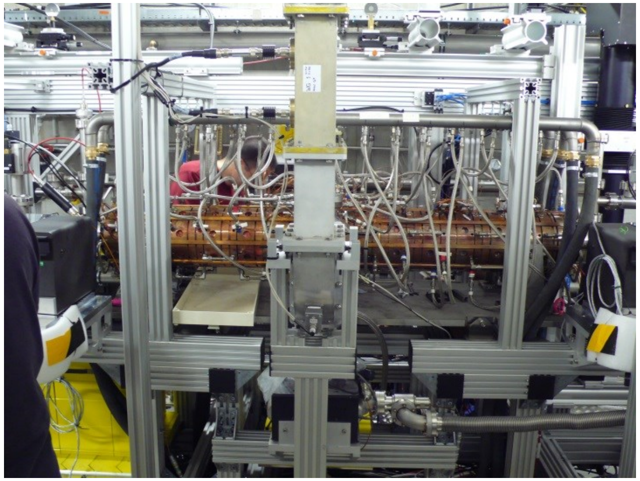
27000 electron bunches per second

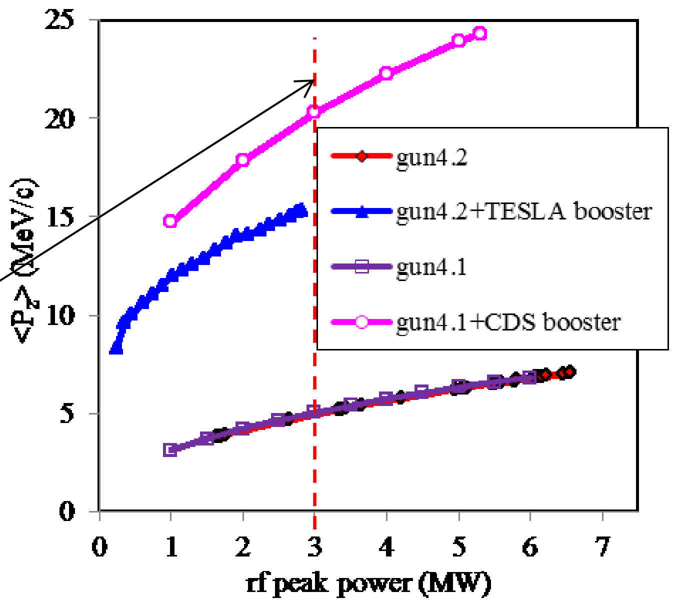
PITZ booster: CDS-cavity

> **CDS booster** (L-band, 14-cell copper Cut-Disc-Structure)

Booster schematic cavity layout.
1 - regular cells,
2 - rf coupler, 3 - rf flanges,
5, 5a - photo multipliers,
6, 6a- vacuum gauges,
7 - pumping ports,
8 - ion pumps,
9 - internal cooling circuit,
10 - outer cooling circuit,
11 - support and adjustment.



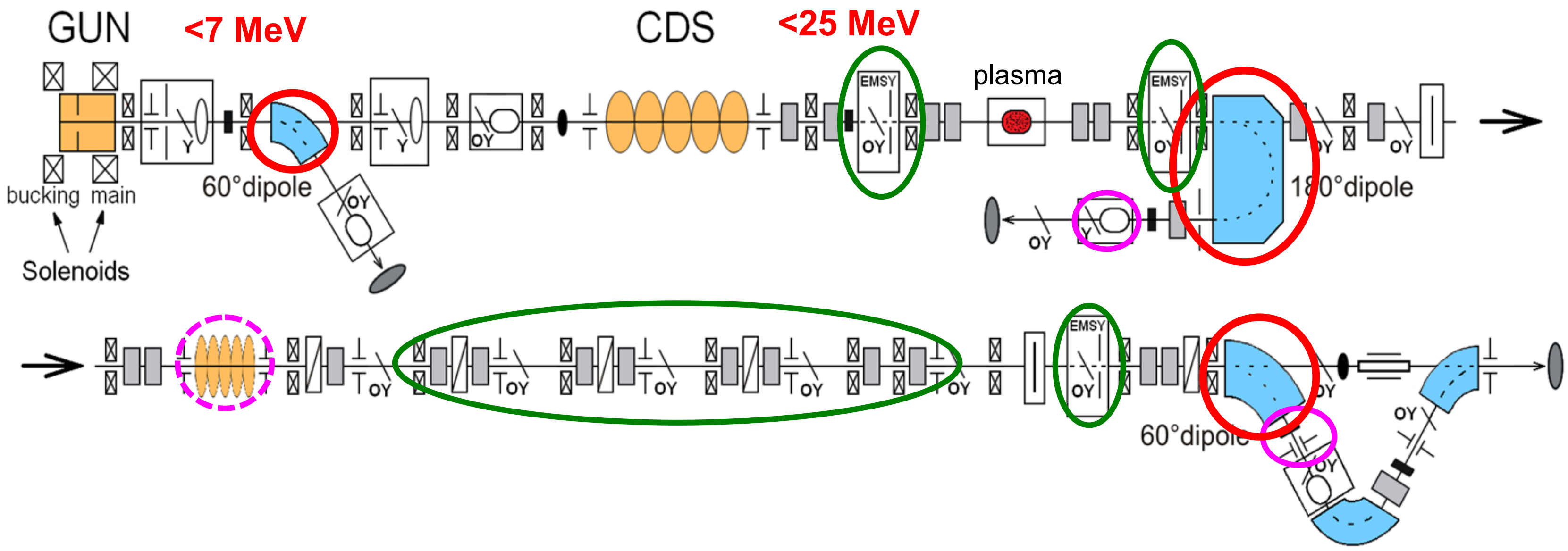




CDS = Cut-Disc-Structure

- improved water cooling system
- higher peak gradients (final beam momentum ~25MeV/c
- long RF pulses (up to 700us)
- longer acceleration (L~1.4m)
- precise phase and amplitude control (RF probes)
- BUT: due to the dark current issue the peak power is currently restricted by 3MW (max)

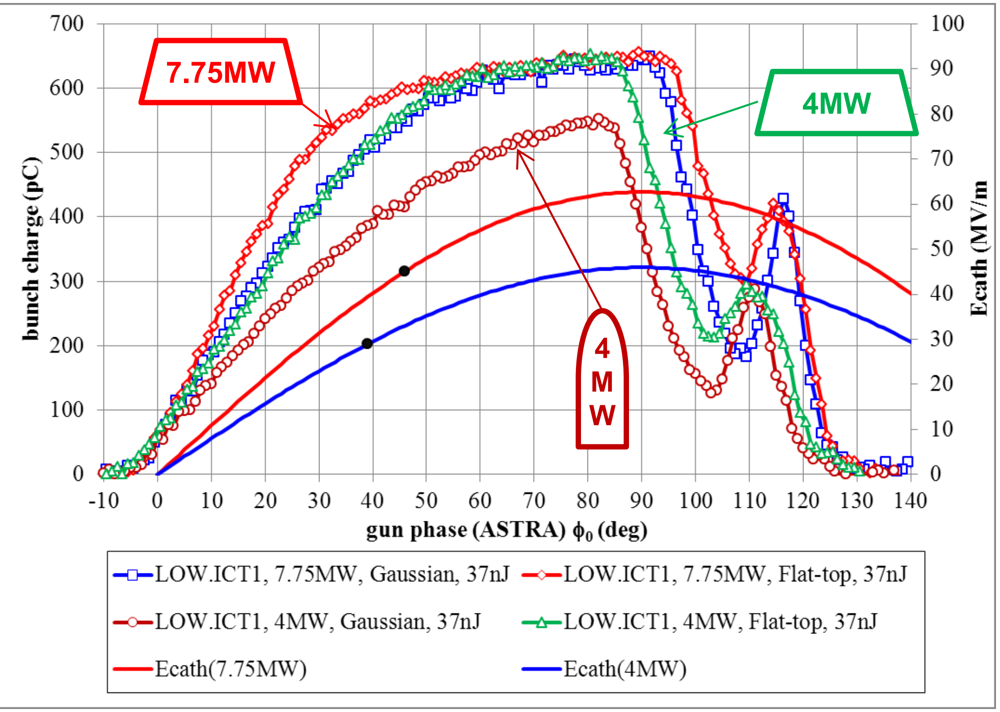
Beam diagnostics at PITZ



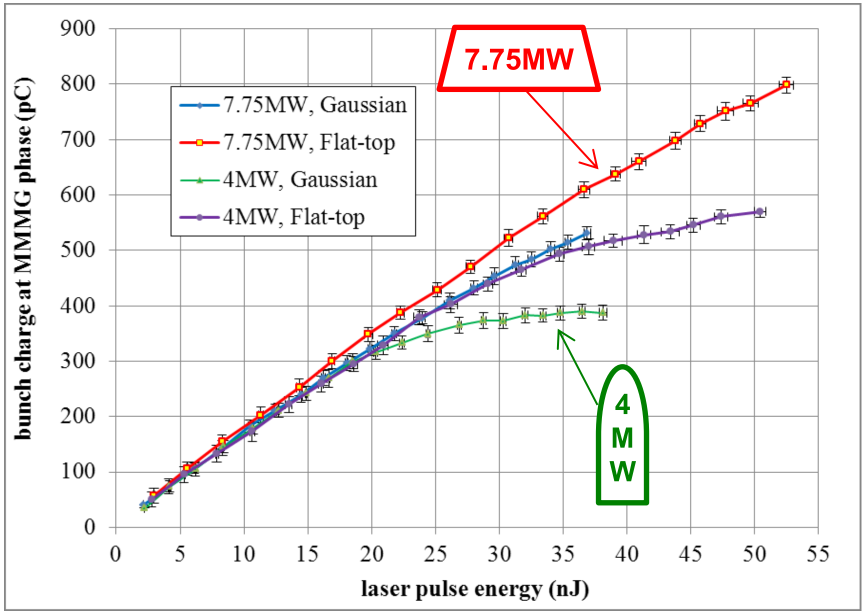
Component	Property	Diagnostics
Cathode laser	temporal profile	OSS, streak-camera
	transverse distribution	Virtual cathodes, CCD cameras
	pulse energy	Energy-meter, PMT
	position stability	Quadrant-diode
Electron beam	bunch charge	Faraday cups (~1pC<FC<200pC), Integrating current transformers (100pC<ICT<5nC)
	beam position	BPMs (Q>200pC)
	longitudinal momentum	**Dipoles+ dispersive arms (LEDA, HEDA1,2)**
	transverse distribution	YAG and OTR screens with CCD cameras (LOW.Scr1,2,3; High1.Scr1-5; PST.Scr1-5; High2.Scr1,2)
	transverse phase space (emittance)	**Slit masks (EMSY1,2,3), quadrupoles, tomography module**
	Bunch current profile	Radiators (straight section) + streak read-out*, Transverse Deflecting System (TDS)
	longitudinal phase space	**Radiators (dispersive arms) + streak read-out*, TDS+HEDA2 (slice energy spread), LPS tomography using CDS phase scan**
	slice emittance	HEDA with booster off-crest, TDS+quad scan at PST-screens

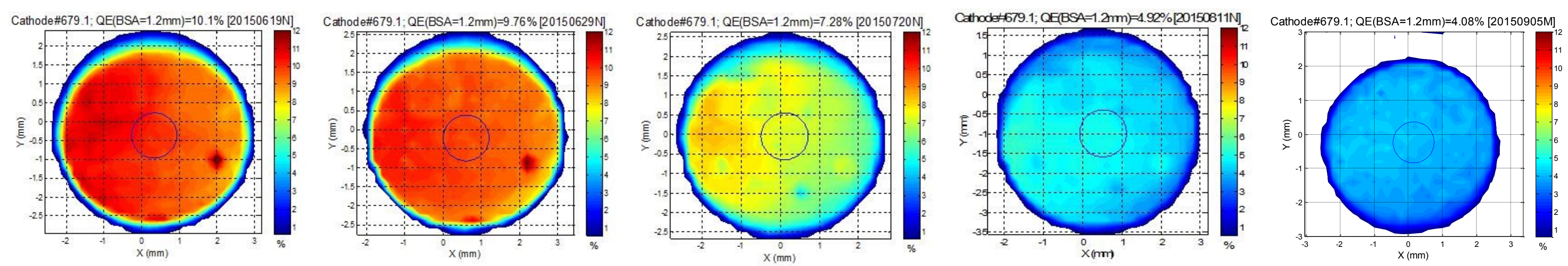
Bunch charge measurements

Schottky scan → Q (rf gun phase)



Laser pulse energy scan → Q (LT)



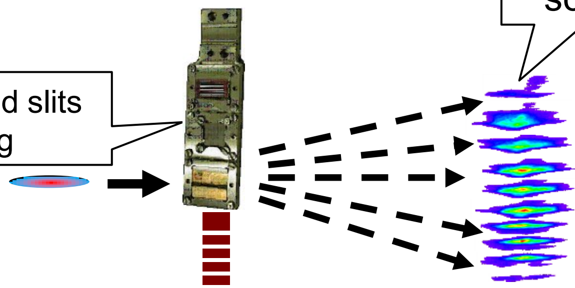


Cathode #679.1 QE-map history

Slit Scan Technique for Emittance Measurements at PITZ

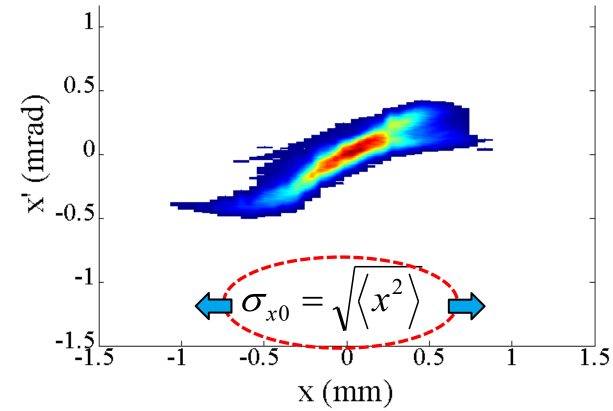
Emittance **M**easurement **SY**stem

EMSY: screens and slits
10 (50) μm opening

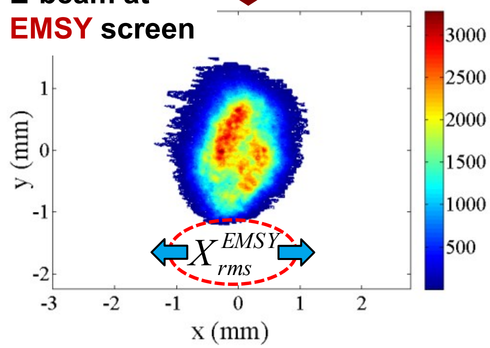


Beamlet collector screen

measured transverse phase space



E-beam at EMSY screen



As conservative as possible!

$$\varepsilon_x = \beta\gamma \frac{X_{rms}^{EMSY}}{\sigma_{x0}} \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$

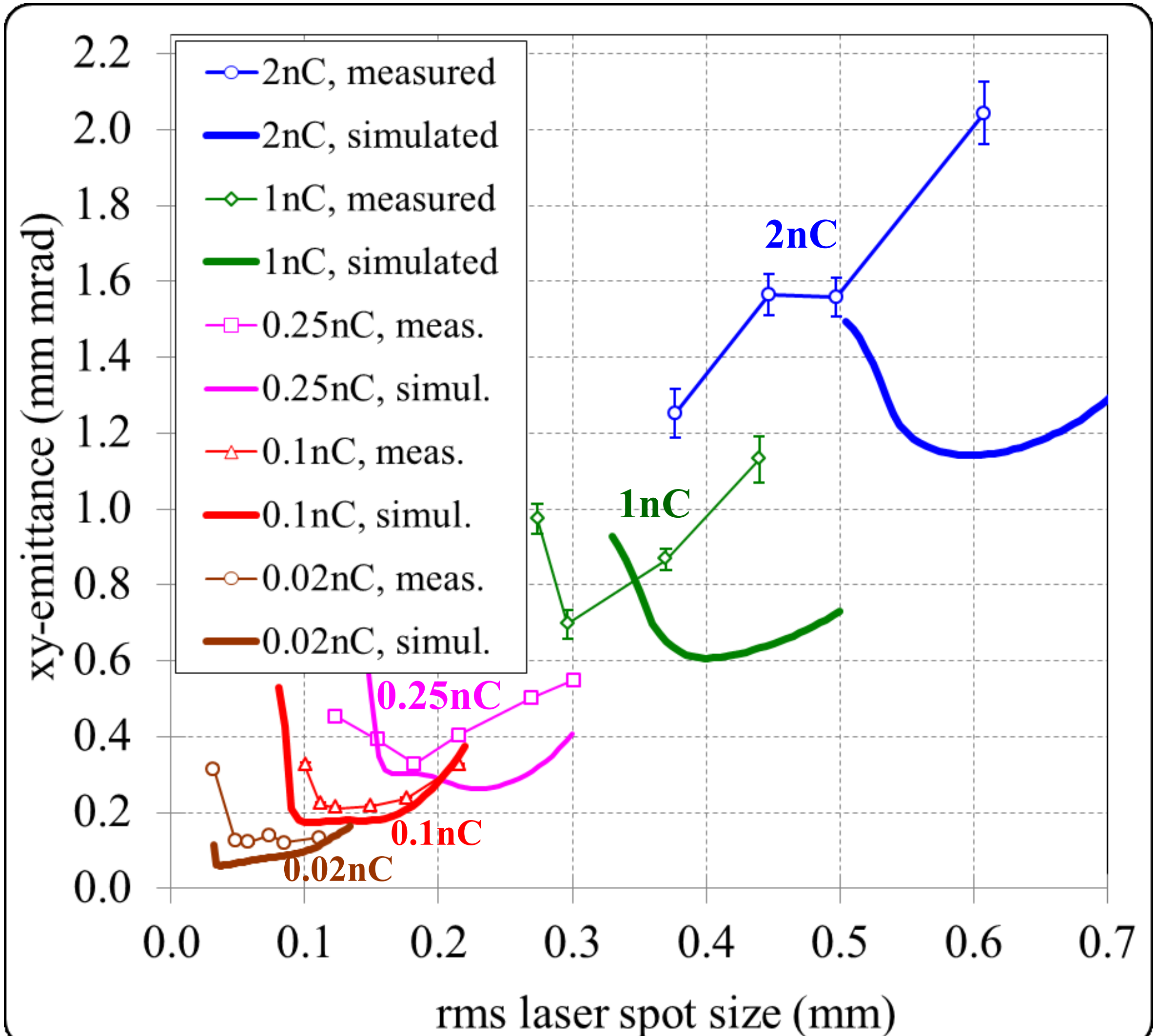
"100%" rms emittance

Correction factor introduced to correct for low intensity losses from beamlet measurements

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

2011: Emittance versus Laser Spot Size for various charges

Measured (100%) rms normalized emittance vs. simulations



Minimum emittance ($\sqrt{\varepsilon_{n,x}\varepsilon_{n,y}}$)

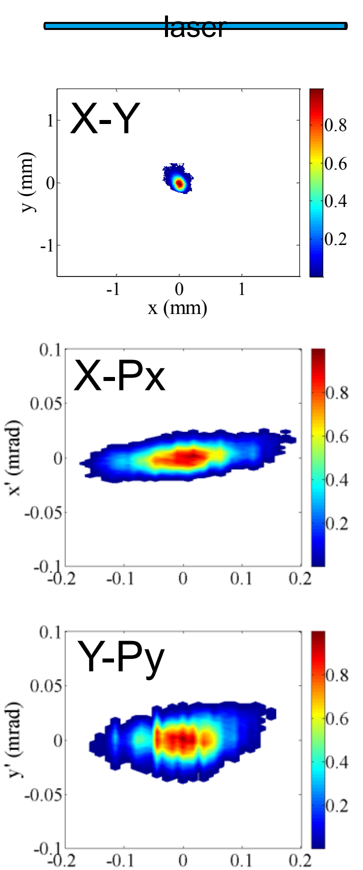
Charge, nC	Measured, mm mrad	Simulated, mm mrad
2	1.25±0.06	1.14
1	0.70±0.02	0.61
0.25	0.33±0.01	0.26
0.1	0.21±0.01	0.17
0.02	0.121±0.001	0.06

- Optimum machine parameters (laser spot size, gun phase):
  experiment ≠ simulations
- Difference in the optimum laser spot size is bigger for higher charges (~good agreement for 100pC)
- Simulations of the emission needs to be improved

2011: Emittance and Brightness versus Bunch Charge

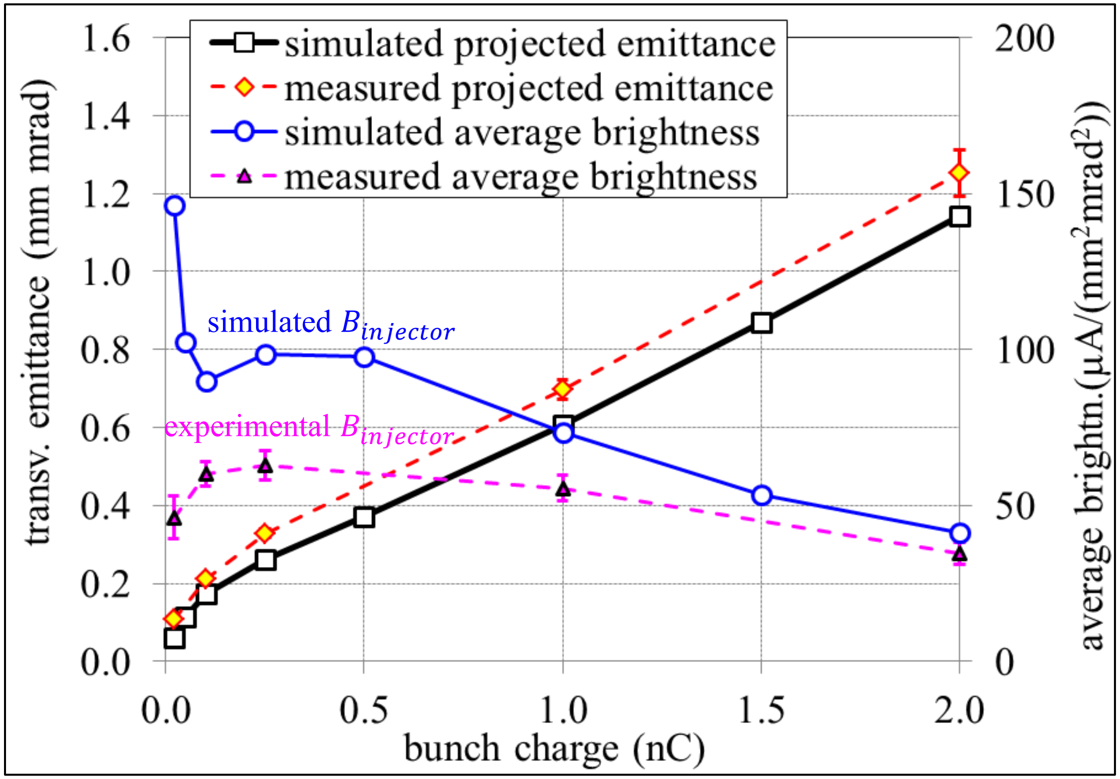
Cathode laser pulse duration was fixed at 21.5 ps (FWHM) for all bunch charges!

20pC measured



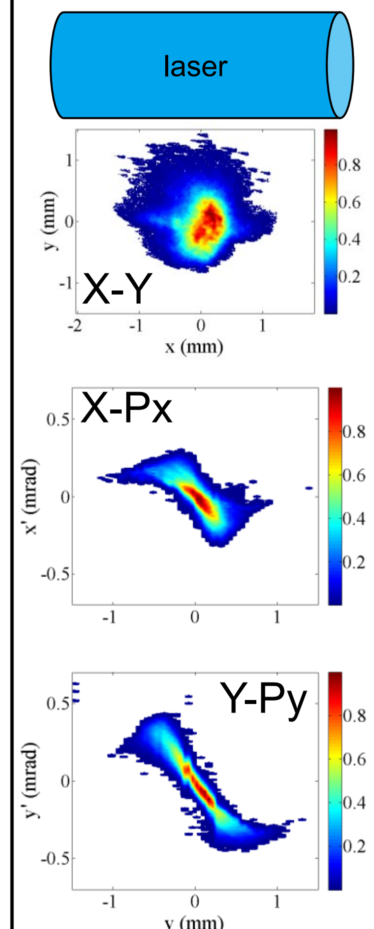
~linear SC

$$B_{injector} = \frac{I_{injector}}{\varepsilon_x \varepsilon_y} = \frac{Q \cdot NoP \cdot RR}{\varepsilon_x \varepsilon_y}$$



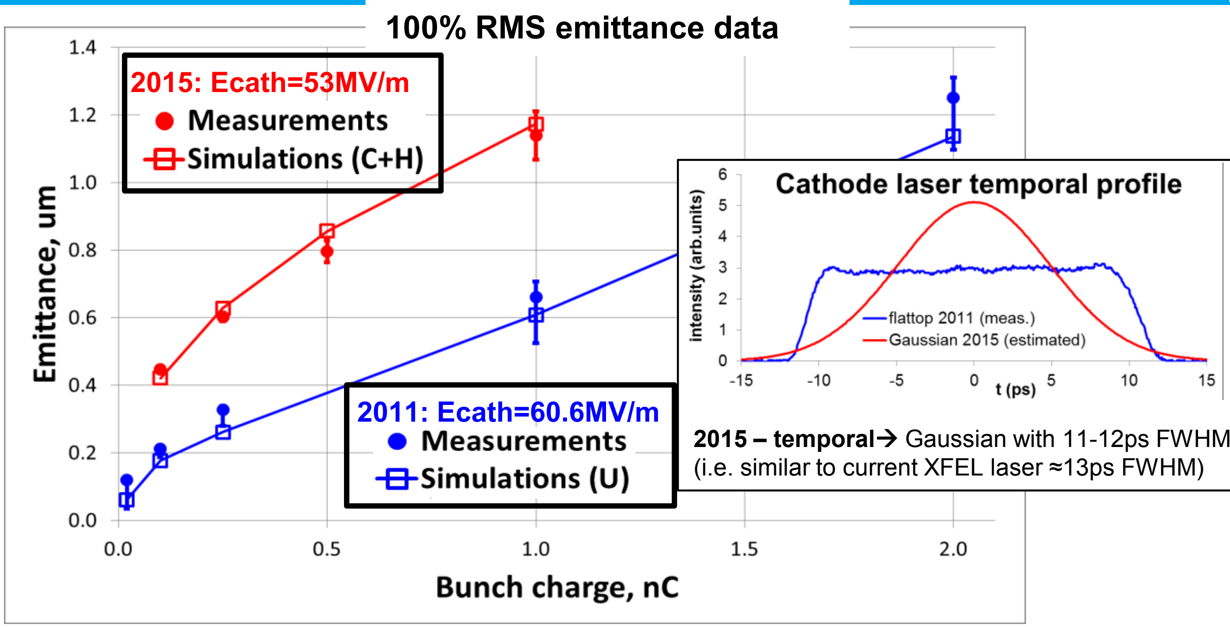
Bunch charge reduction at fixed cathode laser pulse duration → space charge (SC) modification

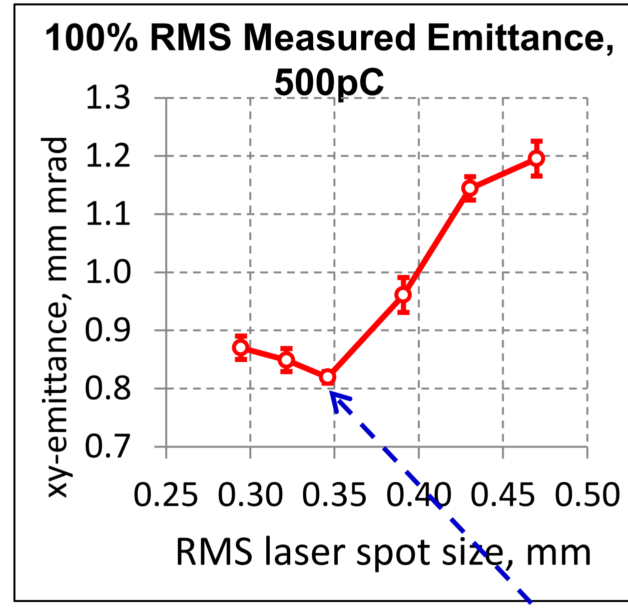
2nC measured



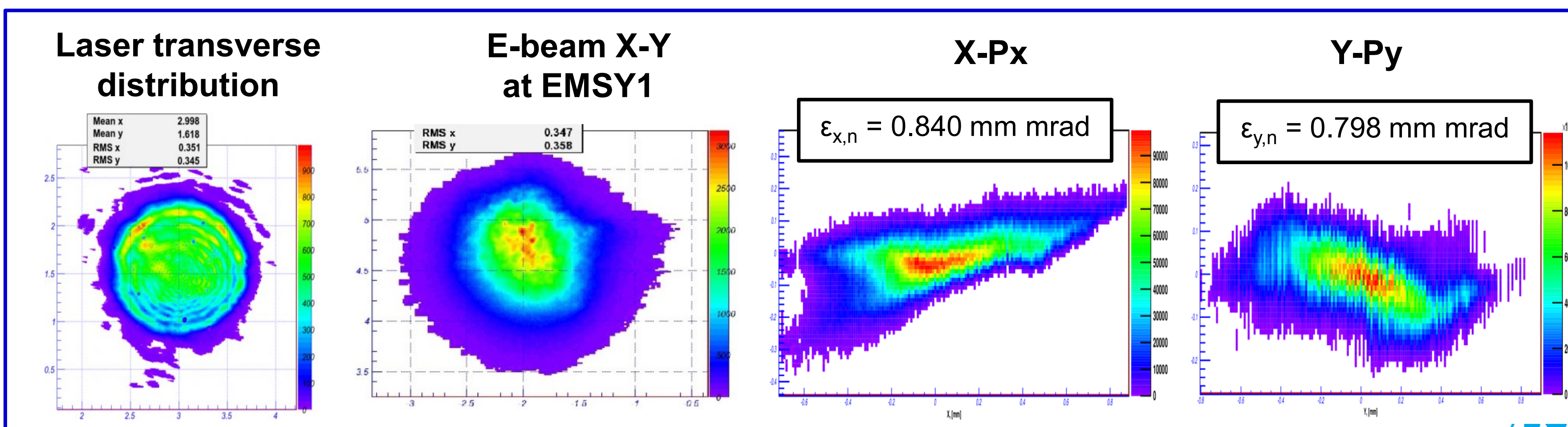
nonlinear SC

Emittance measurements in 2015: Gun at 53 MV/m, Cathode laser → temporal Gaussian

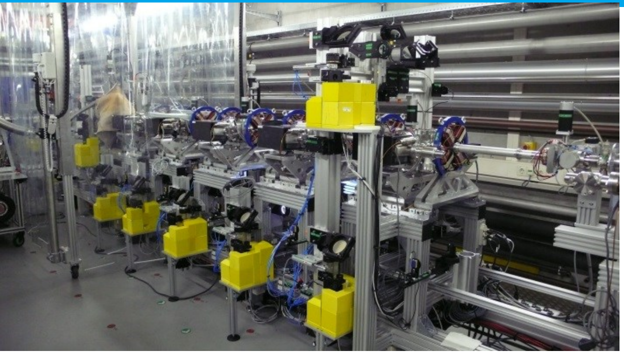


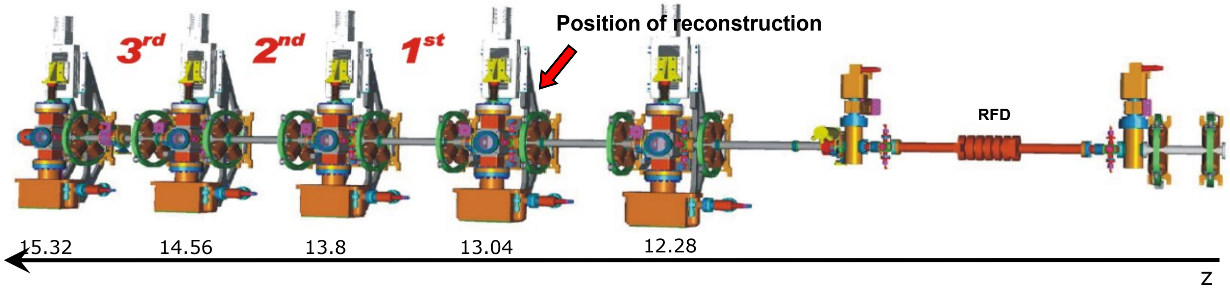


Requirement for XFEL injector commissioning: 1 mm mrad at 500pC ➔ **fulfilled !**

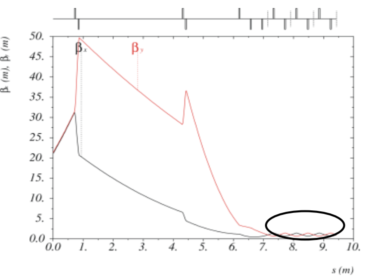


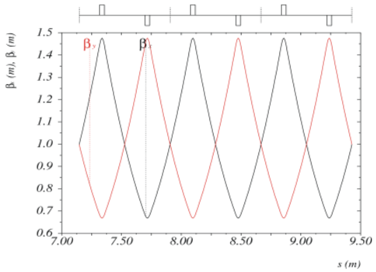
Phase Space Tomography (e.g. at PITZ)

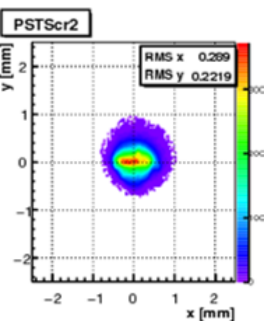


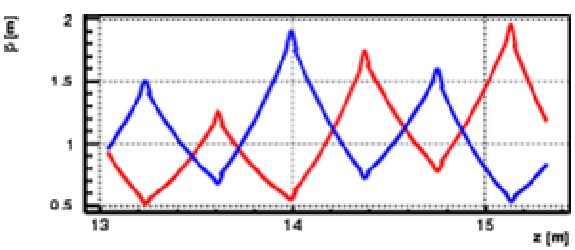


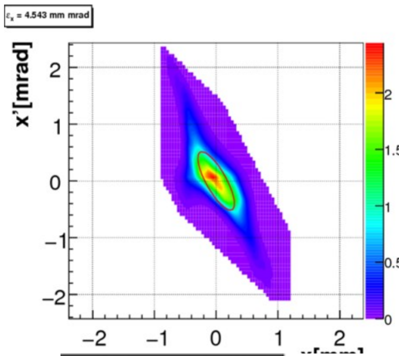
- The most used technique → quadrupole(s) scan, but it yields only Twiss parameters and emittance, not the phase space. Therefore→phase space tomography
  - Back projection
  - Filtered Back projection
  - Algebraic reconstruction technique (ART)
  - Maximum entropy (MENT)

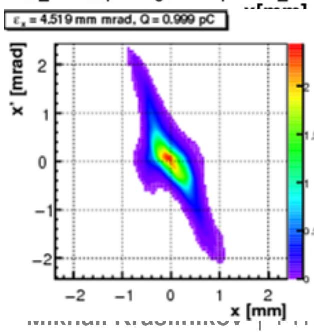


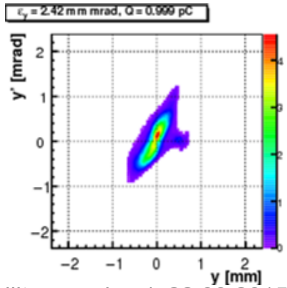












Courtesy G.Asova (PITZ)

Transverse Deflecting System (TDS)

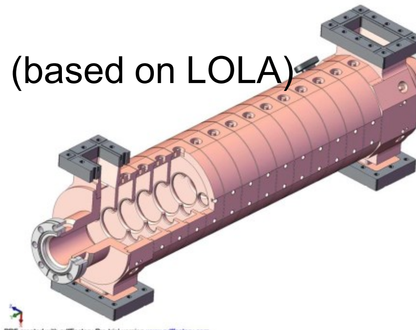
> Prototype for the XFEL injector

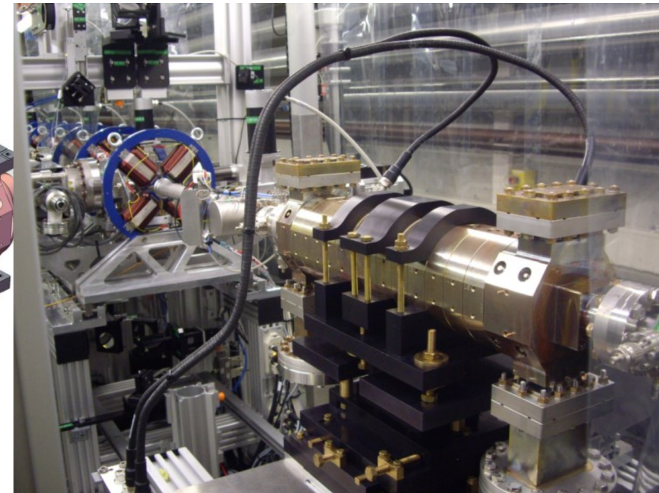
> Designed & manufactured by INR, Troitsk, Russia

> Travelling wave structure (based on LOLA)

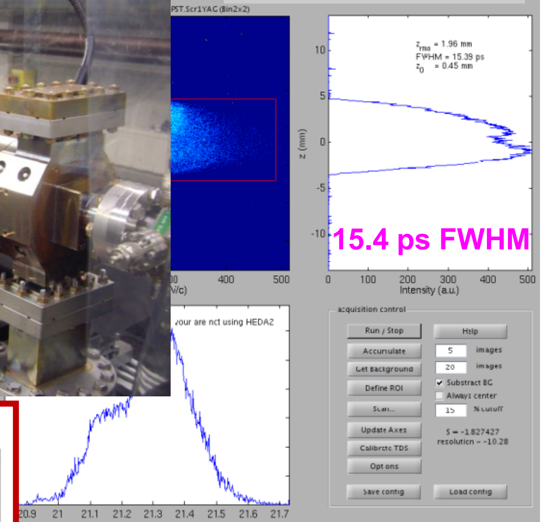
> Design parameters:

- 1.7 MV over 0.533 m
- 14+2 cells (2π/3)
- 2997.2 MHz
- Q = 11780





E-beam current profile

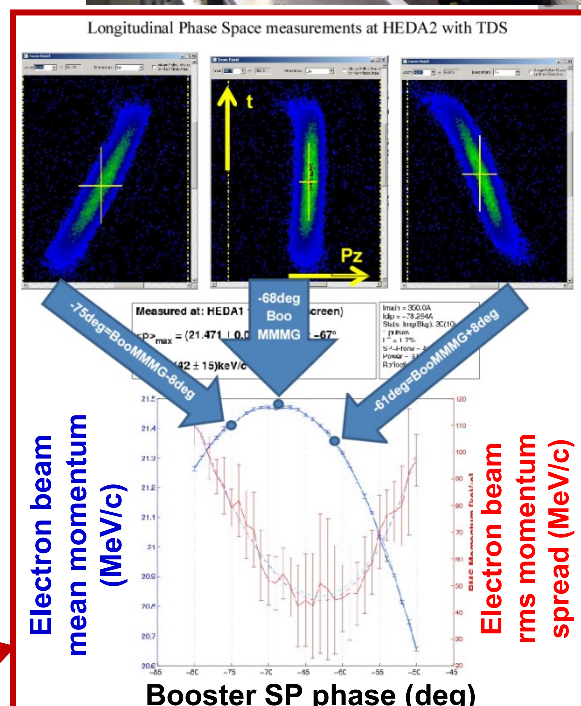


> Expected power balance:

- Q~88% at 45°C, 44 m WG losses…
- 2.1 MW @structure
- 2.7 MW @klystron

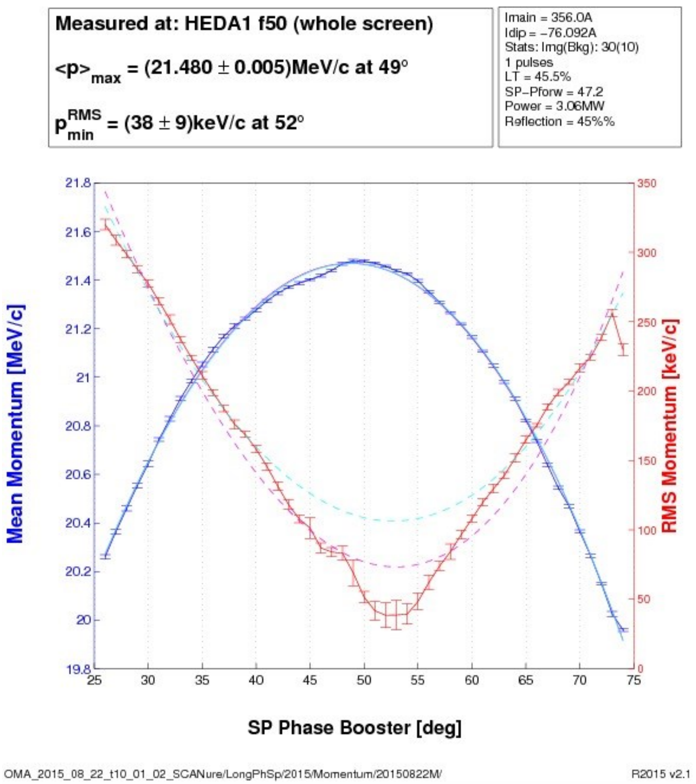
> TDS **commissioning** started on **02.07.2015**!

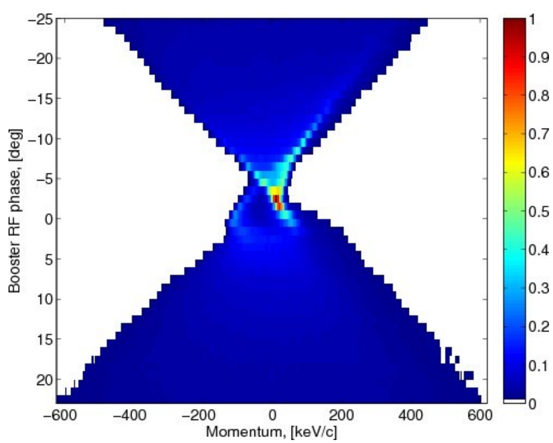
- Structure conditioned up to ~600 kW (~25% of design value).
- **First measurements** taken:
  - Calibration of couplers vs. e-beam deflection
  - Temperature dependencies
  - Bunch length vs. charge and booster phase
  - TDS+HEDA2= single-shot images of **longitudinal phase space**

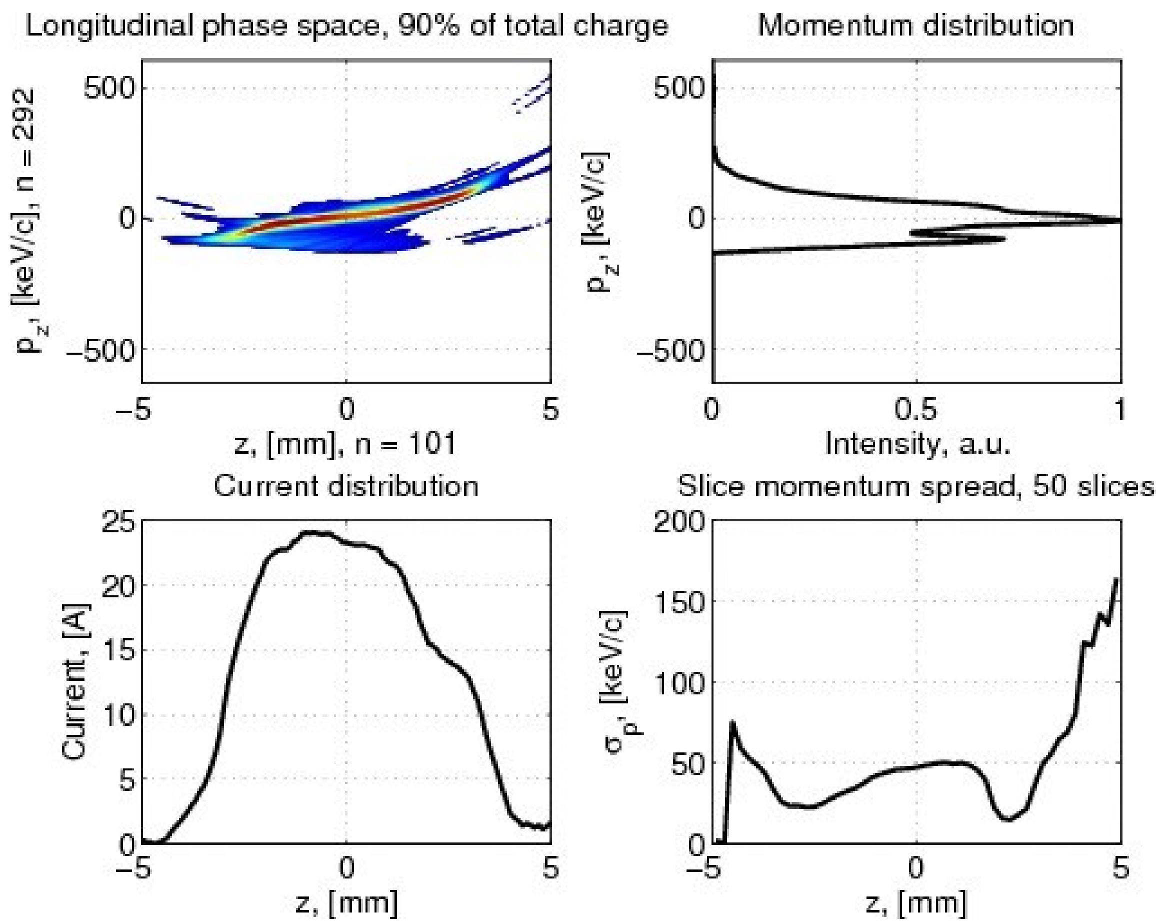


new ScandiNova modulator

Longitudinal Phase Space Tomography with CDS





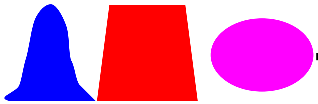


dpz = 4.257 [keV/c]
dz = 0.100 [mm]
RMS bunch length = 1.91 [mm]
RMS momentum spread = 70.39 [keV/c]
Longitudinal Emittance = 90.01 [mm*keV/c]

New Developments at PITZ

- 3D ellipsoidal cathode laser pulses
- Particle driven wake field plasma acceleration exteriment
- THz simulations

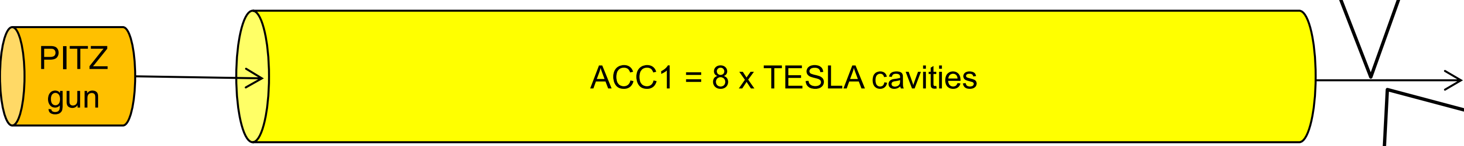
Beam Dynamics Simulations: XFEL Photo Injector (1nC)

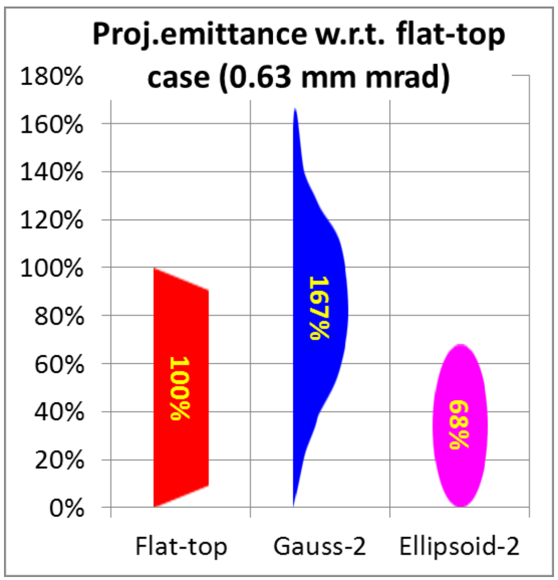


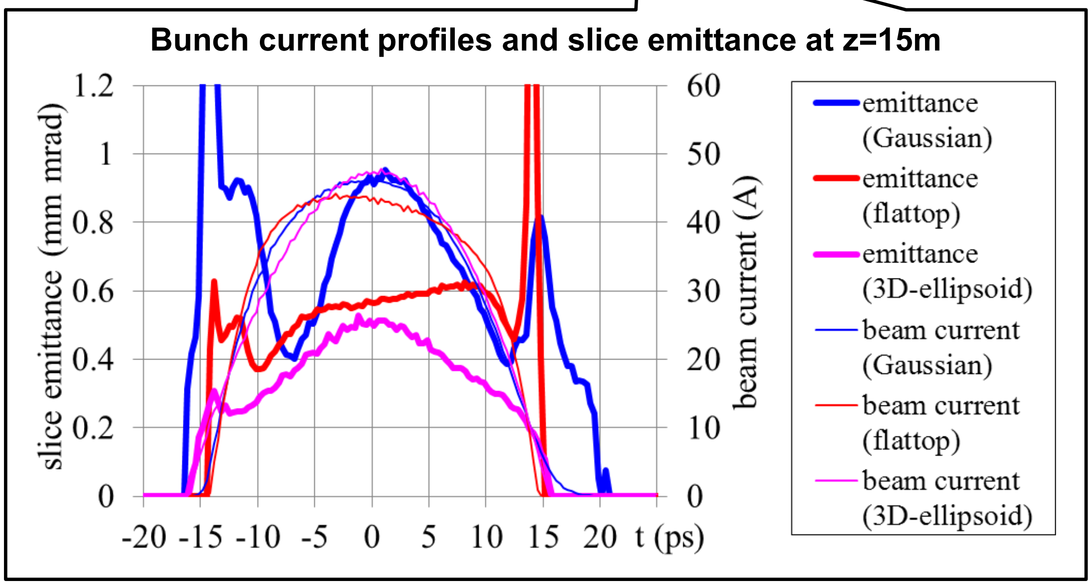
➔Various shapes of the photocathode laser pulse

(Gaussian and Flattop temporal profiles vs. 3D-ellipsoid)

z=15m
E_{beam}~150MeV
σ_t ~7ps



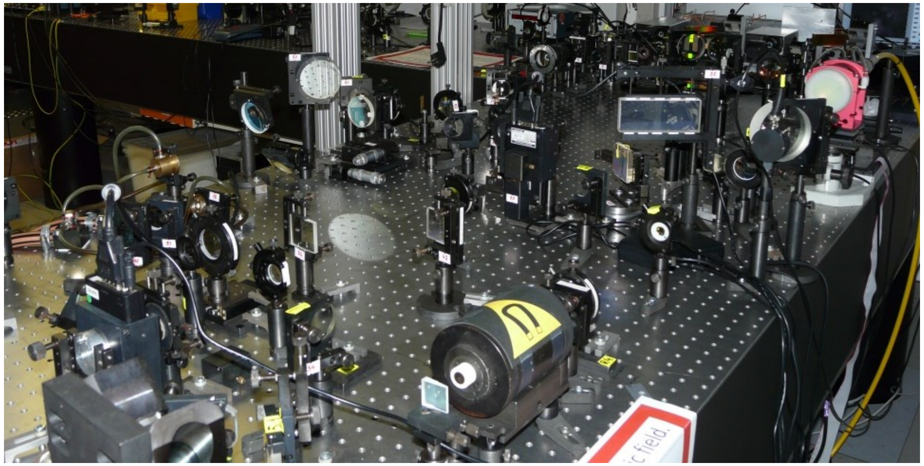




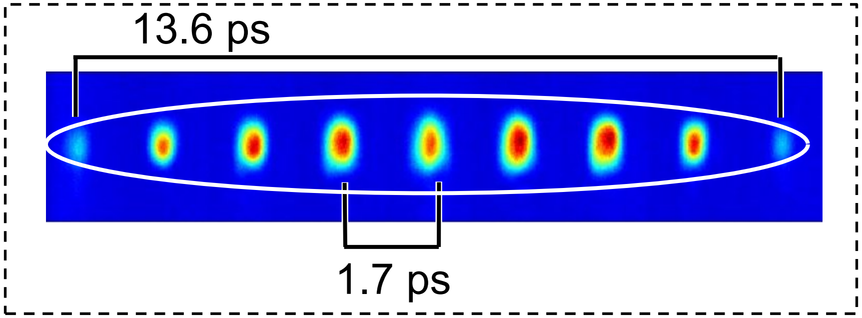
- 3D ellipsoidal cathode laser pulses ➔ Major improvements on beam emittance
- Developments of the new laser system are on-going → DESY (PITZ)+IAP+JINR collaboration

New photocathode laser system for 3D ellipsoidal pulses

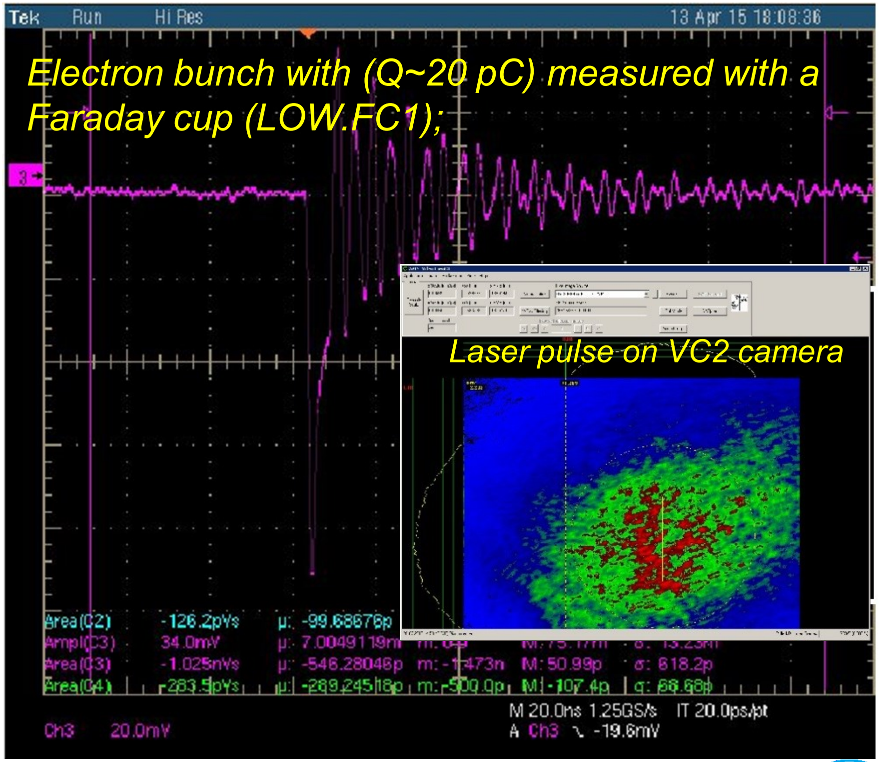
- Installation finalized 12/2014

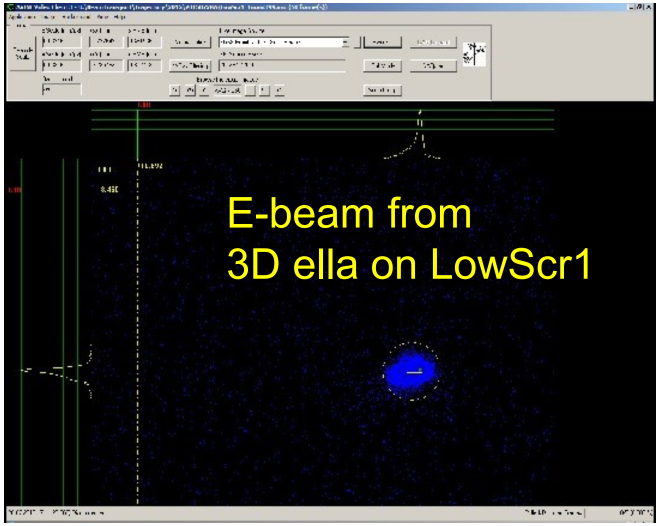


- Commissioning begun 2015
- First photoelectrons 04/2015
- Beamline finalized 04/15



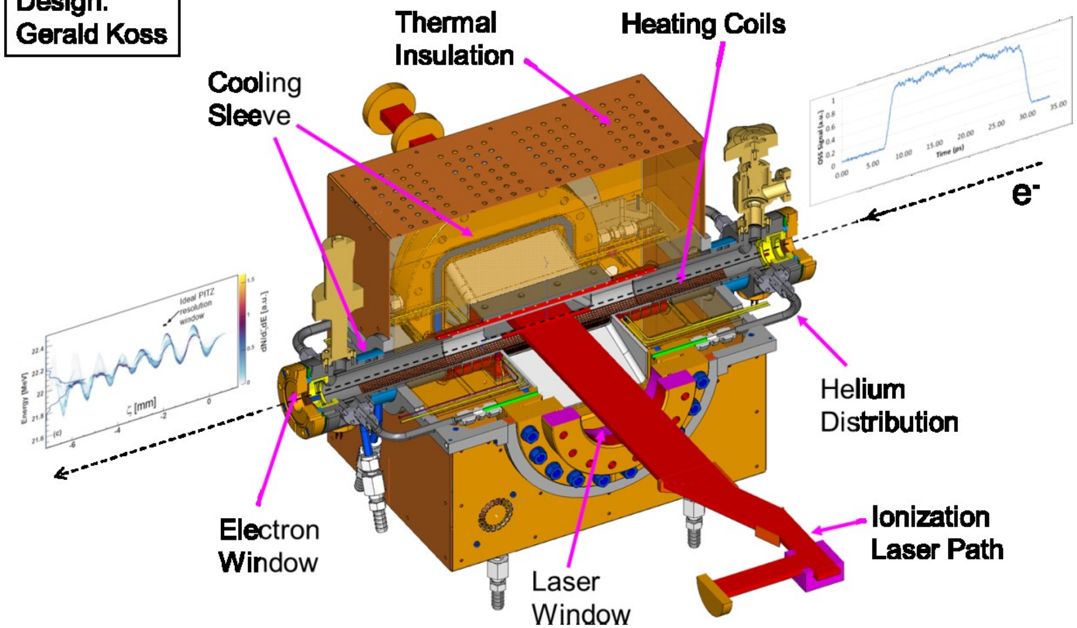
Cross-correlation measurement of pulse



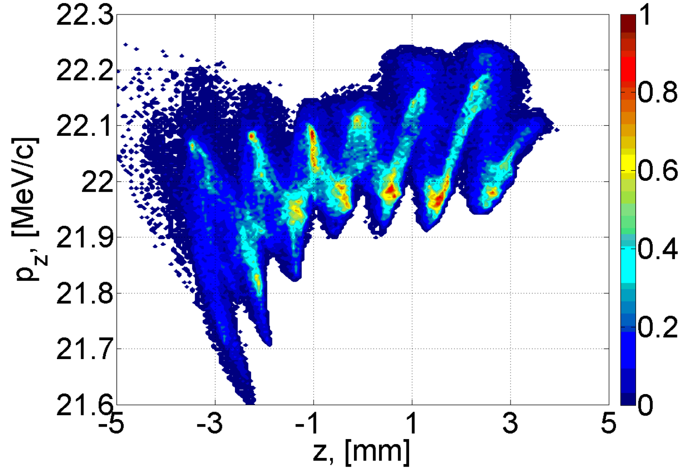


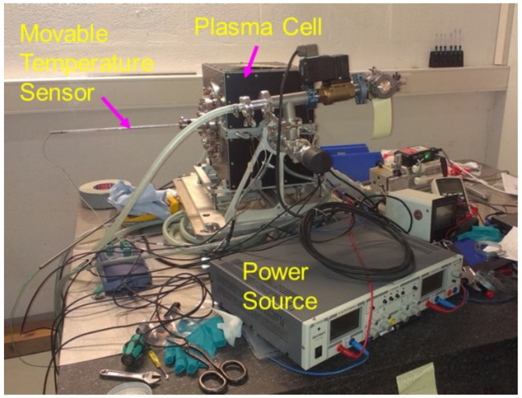
Self-modulation Experiment with long Electron Beams

Design: Gerald Koss

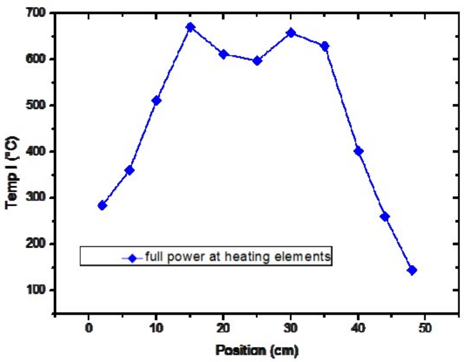


Simulation of experiment: Expected phase space





Measurement of longitudinal temperature profile



- PITZ plasma cell:
  - designed and fabricated
  - commissioning mainly done (next step: Lithium vaporization, ionization)
  - leaky plasma cell is being repaired
- PITZ beamline was remodeled
- Ionization laser is set up
- Several preparatory experiments performed:
  - <100μm focusing into plasma cell
  - 8μm Kapton foil → for first experiments, 3μm ➔ goal for the window thickness (from BD simulations and first experiments)

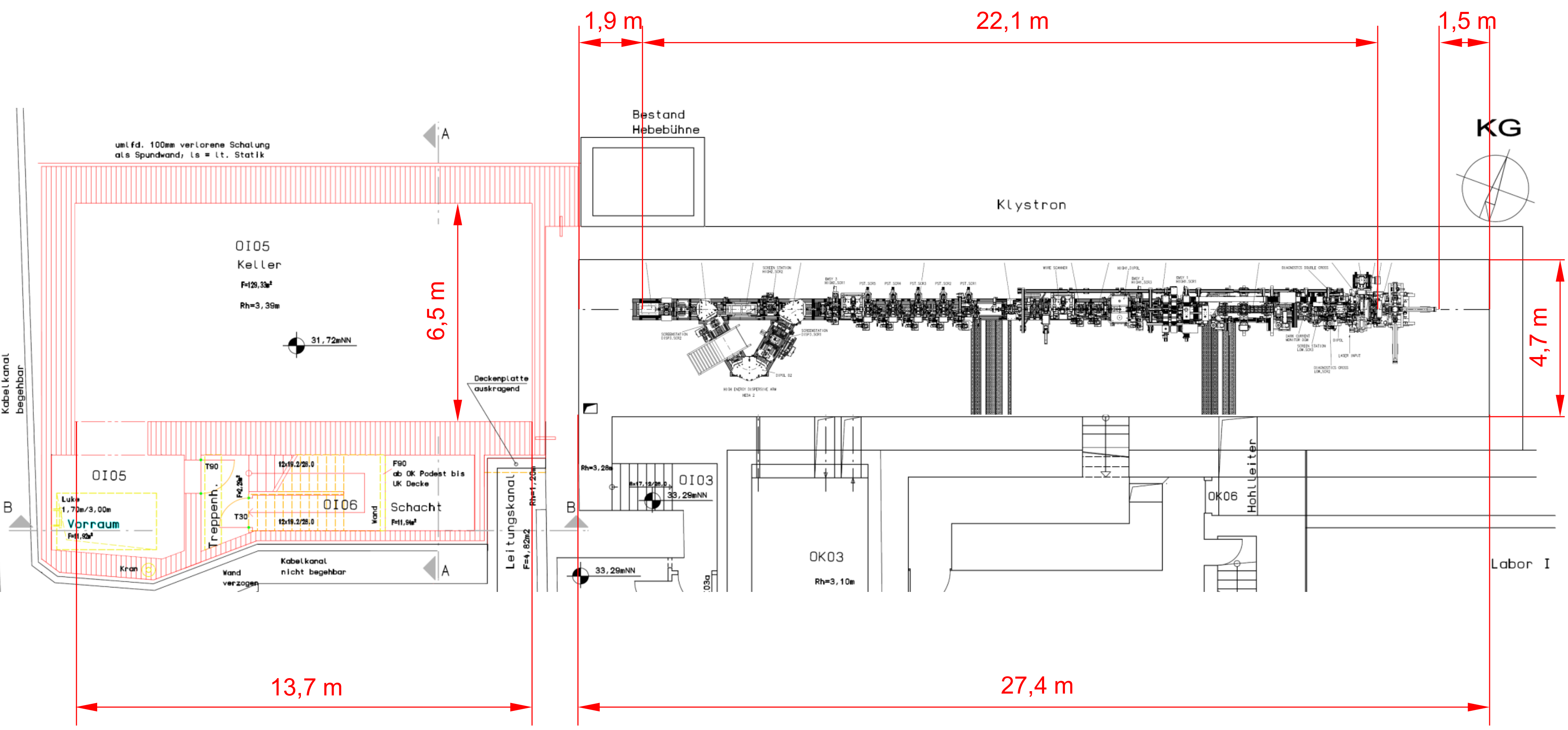
Conclusions and Outlook

- The Photo Injector Test facility at DESY in Zeuthen (PITZ) develops high brightness electron sources for SASE FELs:
  - specs for the European XFEL have been demonstrated and surpassed (emittance <0.9 mm mrad at 1nC)
  - beam emittance has also been optimized for a wide range of bunch charge (20pC…2nC)
  - Now main focus → stability and reliability (high duty factor performance)

- PITZ serves also as a benchmark for theoretical understanding of the photo injector physics (beam dynamics simulations vs. measurements)
  - Emittance
  - Photoemission
  - Imperfections!

- Outlook → new developments:
  - slice diagnostics (RF deflector) → transverse emittance and longitudinal phase space (ongoing)
  - 3D ellipsoidal cathode laser pulses ➔ BMBF and HGF projects (collaboration DESY-IAP-JINR)
  - PDPWA experiments
  - THz option ➔ simulations + brainstorming (this mini-WS = kick off meeting)

PITZ tunnel(s)



Backup slides

XFEL Photo Injector Performance Requirements → PITZ

subsystem	parameter	*value*	remarks
RF gun cavity	frequency	*1.3 GHz*	L-band 10MW MBK
	E-field at cathode	***60 MV/m***	dark current issue
	RF pulse duration	*650 us*	max
	Repetition rate	*10 Hz*	max
Cathode laser	Temporal –> flat top –> FWHM	***~20 ps***	**challenge** ~20ps
	Temporal –> flat top –> rise/fall time	***2 ps***	
	Transverse – rad.homogen.XYrms	*0.3-0.4 mm*	fine tuning -> **thermal emittance**
	Pulse train length	*600 us*	max
	Bunch spacing	*222 ns (4.5MHz)*	1us (1MHz) at PITZ now
	Repetition rate	*10 Hz*	max
Electron beam	Bunch charge	*1 nC*	**0.02-1nC (Post-TDR)**
	Projected emittance at injector	***0.9 mm mrad***	→ for 1 nC
	Bunch peak current	*5 kA*	after bunch compression (not at PITZ)
	Emittance (slice) at undulator	***1.4 mm mrad***	**0.4-1.0 mm mrad (Post-TDR)**