The Photo Injector Test Facility at DESY in Zeuthen

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for the PITZ collaboration

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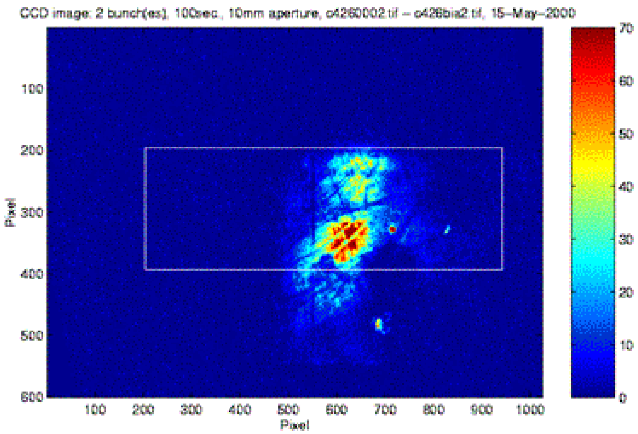
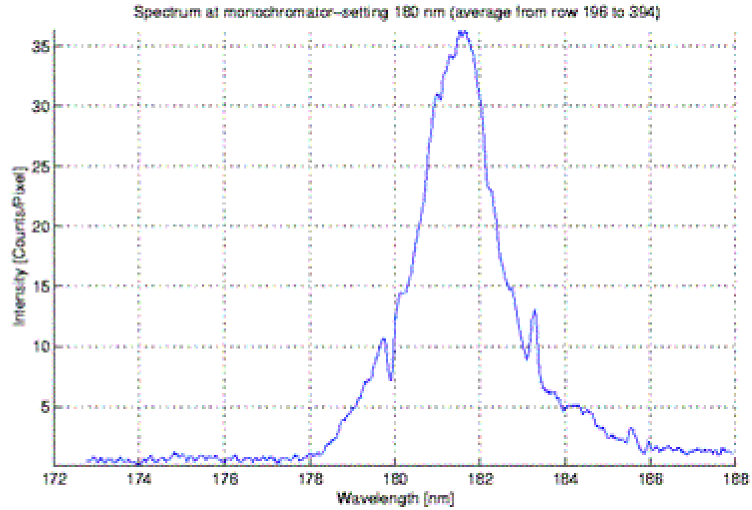
Overview

- **Motivation: VUV-FEL and XFEL**
  → photo injector R&D for DESY's FELs
- **The photo injector at Zeuthen**
  → a brief history of PITZ
- **The PITZ1 research program**
  → presentation of the PITZ1 results
- **Facility upgrade: towards PITZ2**
  → current status and future plans
- **Summary**

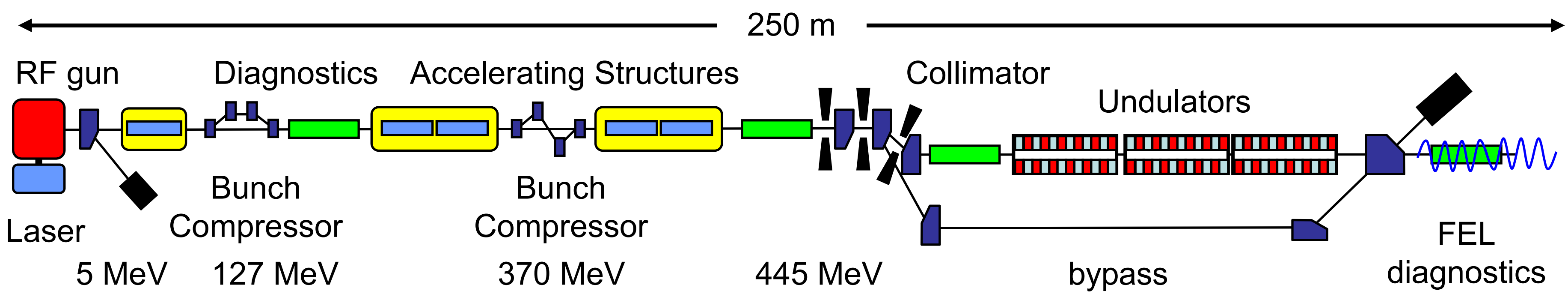
FELs at DESY

- **TTF1** has reached SASE in 2000

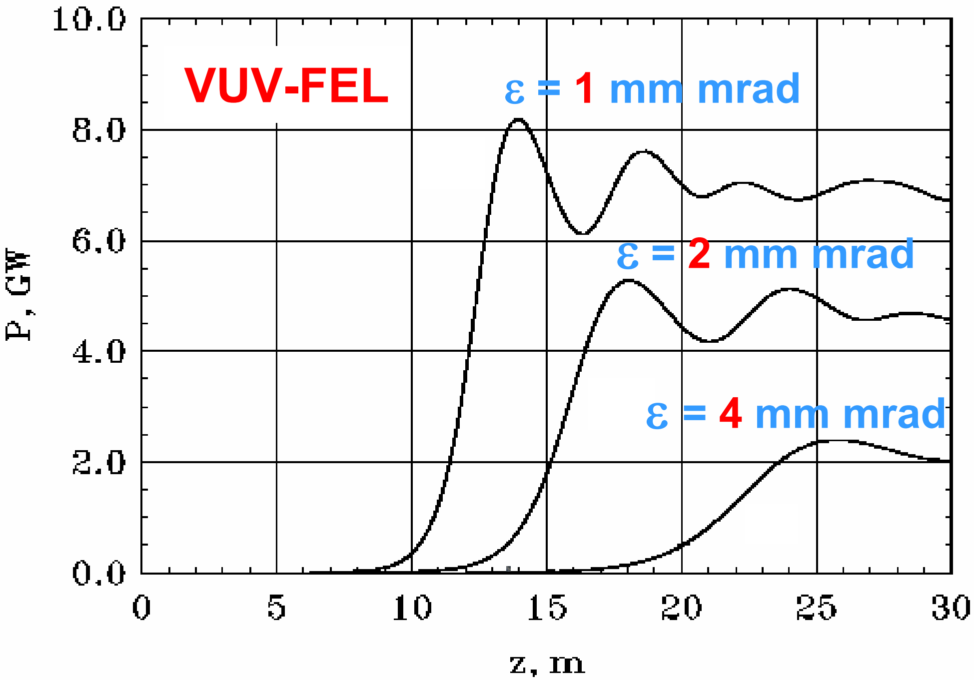


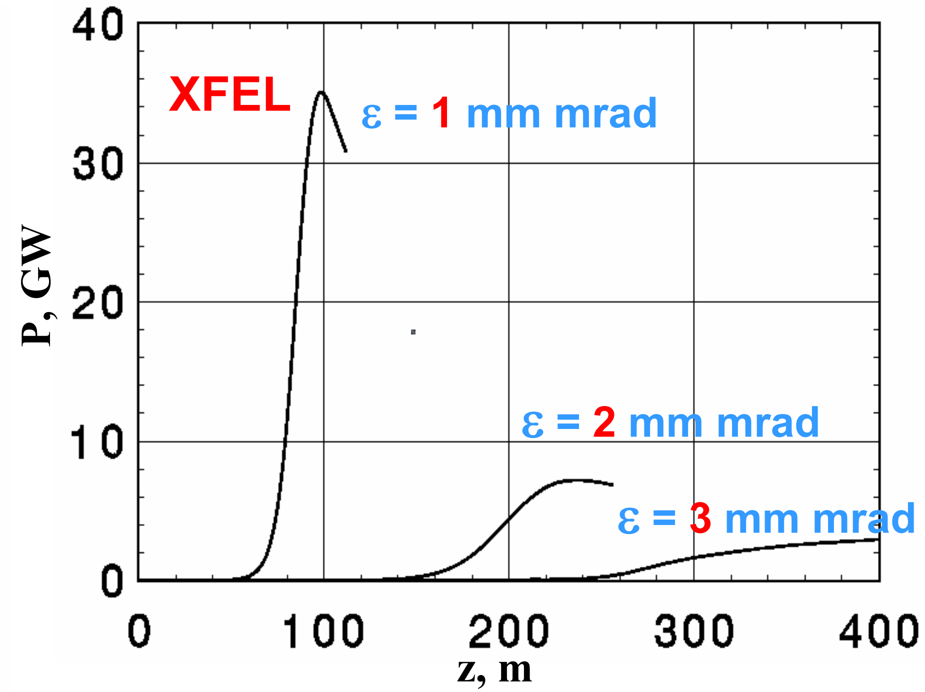


- **VUV-FEL** is running as user facility since August 2005



FELs at DESY





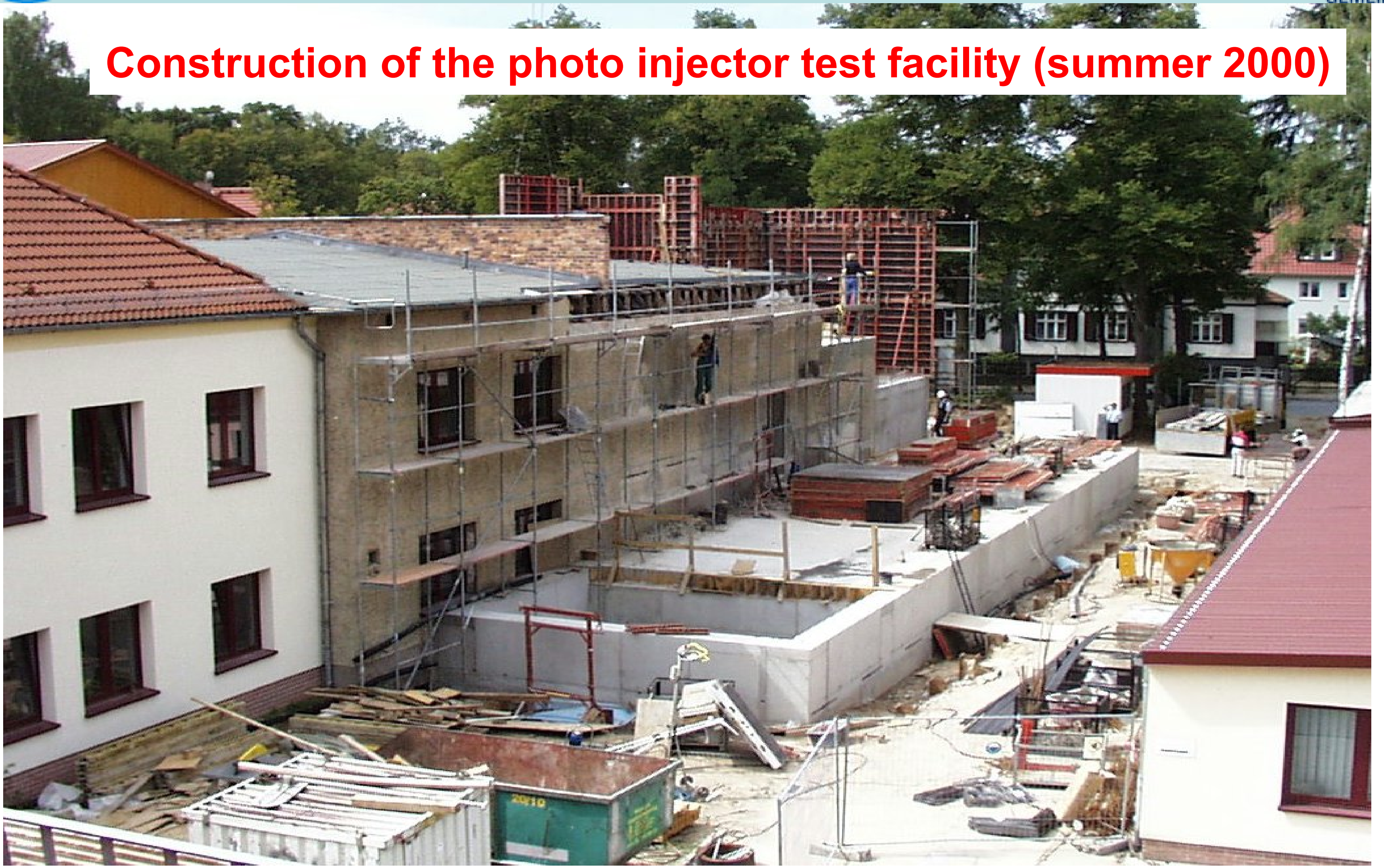
- performance of the planned **XFEL** (>2012) depends strongly on the electron beam quality of the injector
- beam quality can only detoriate in the accelerator
- electron source must provide very small emittance beam
- photo injector development is urgent

The PITZ project

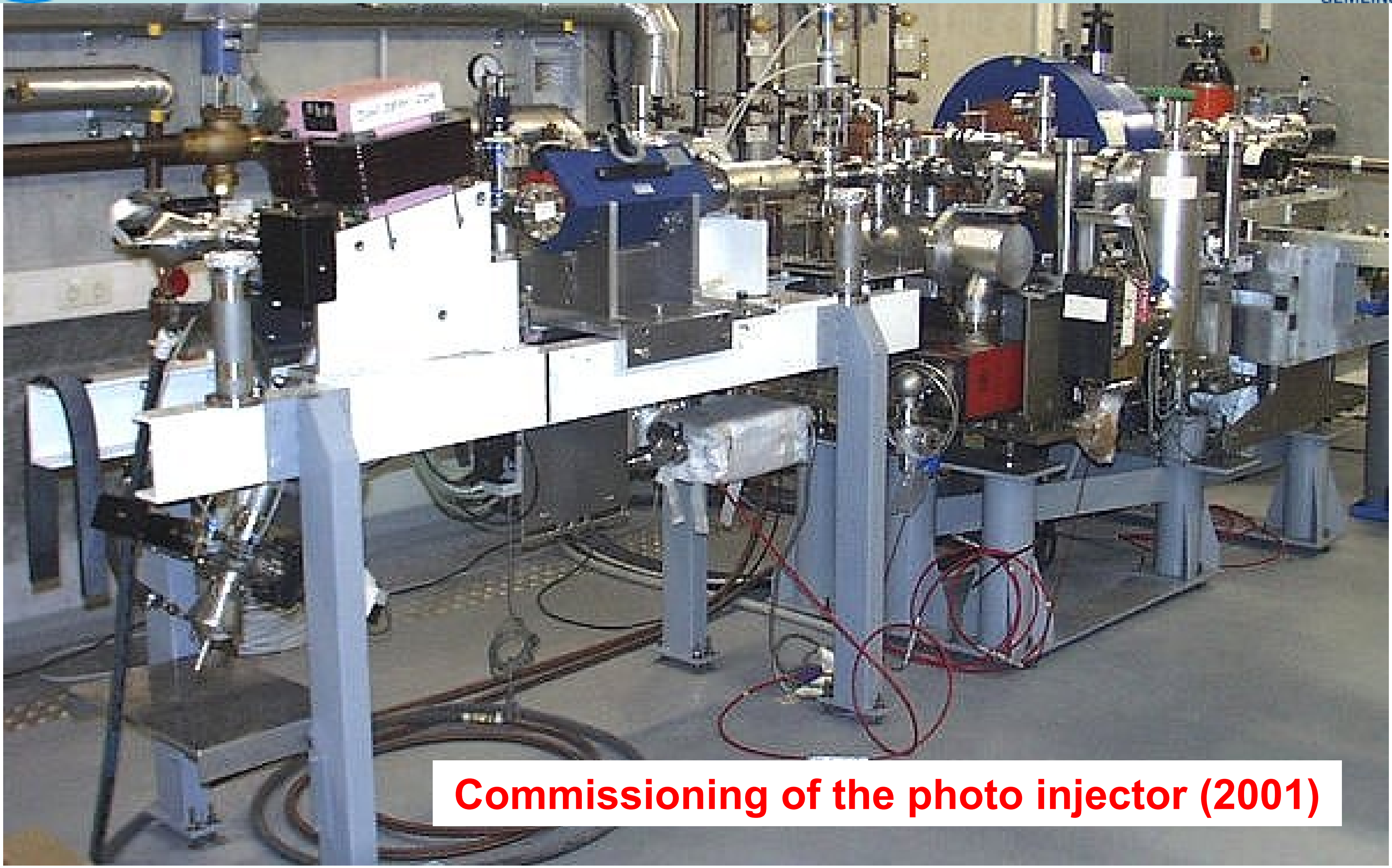
→ construction of a **Photo Injector Test facility** in **Z**euthen with the goals:

- 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 concrete FEL / user requests
- compare detailed experimental results with simulations:
  → benchmark theoretical understanding of photo injectors
- prepare rf guns for subsequent operation at VUV-FEL / XFEL
- test new developments (laser, cathodes, beam diagnostics)
- long term plans: e.g. flat beams, polarized electrons for ILC

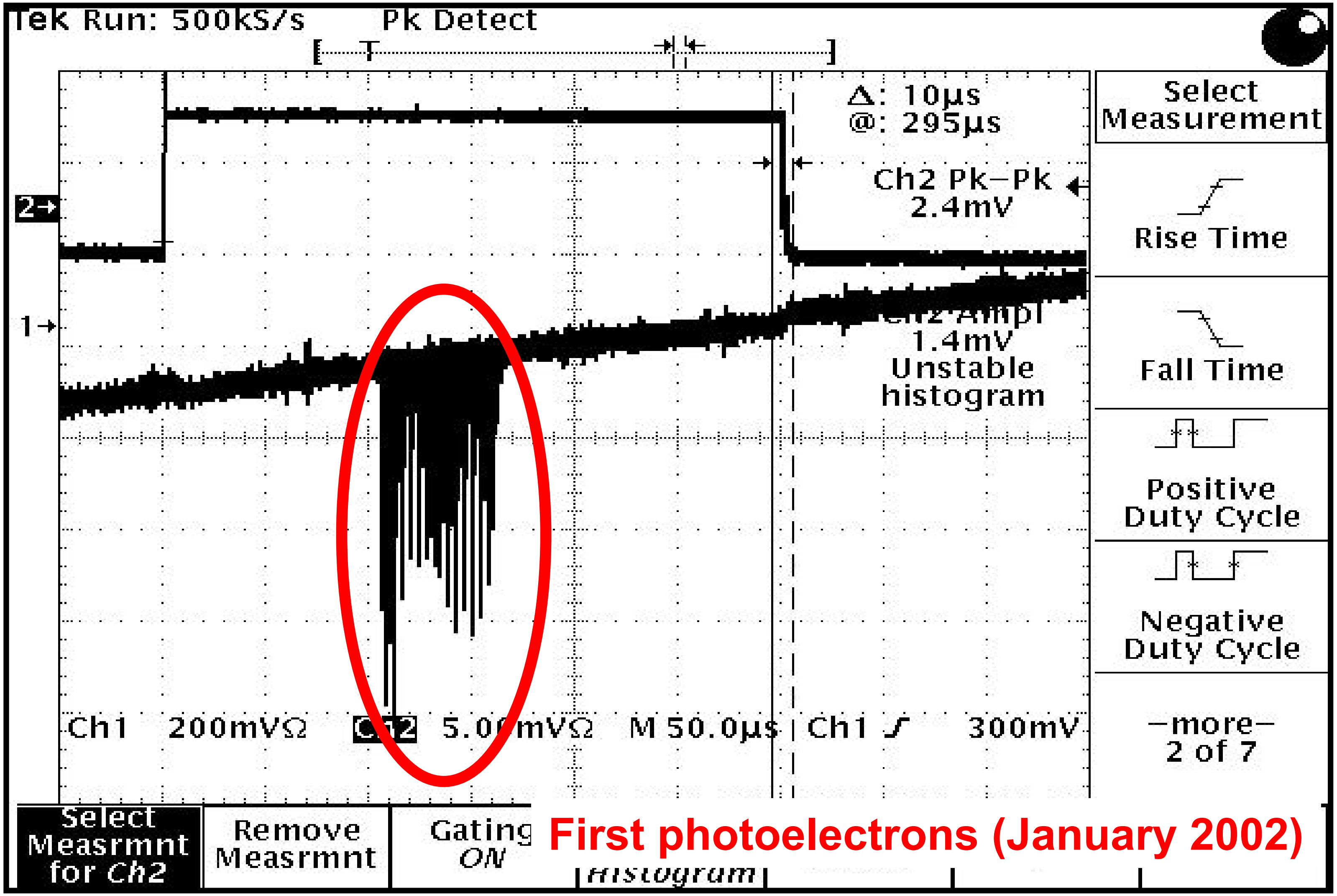
The PITZ project



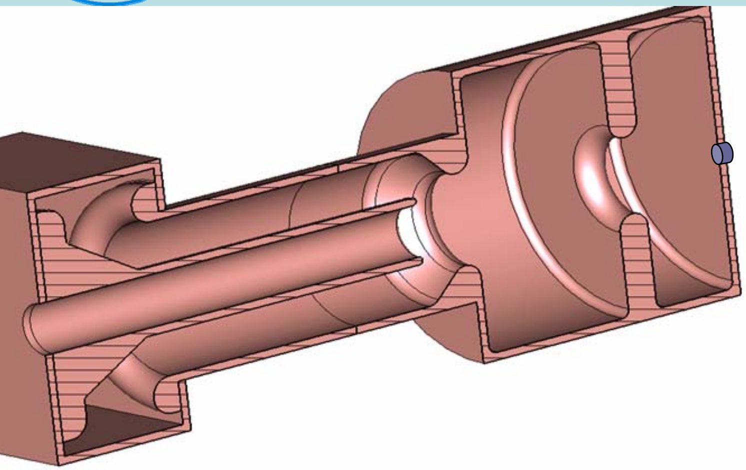
The PITZ project



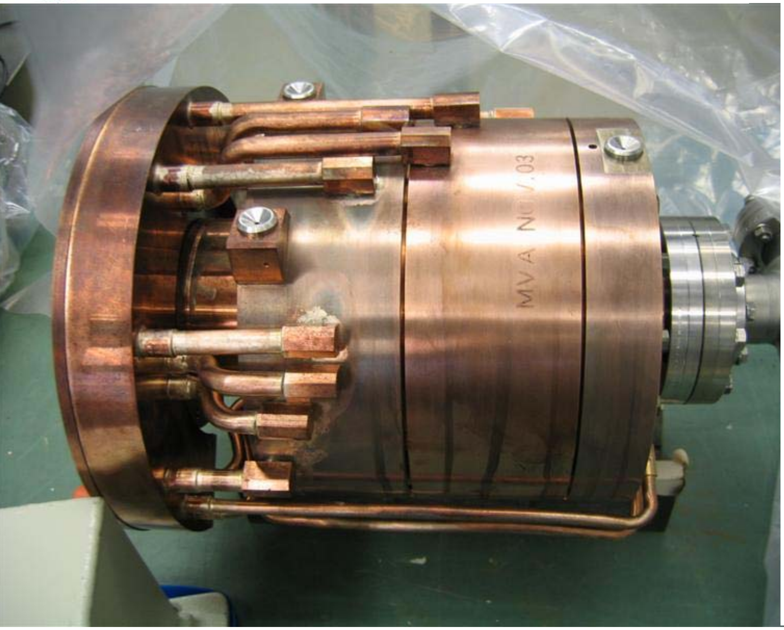
The PIT Z project

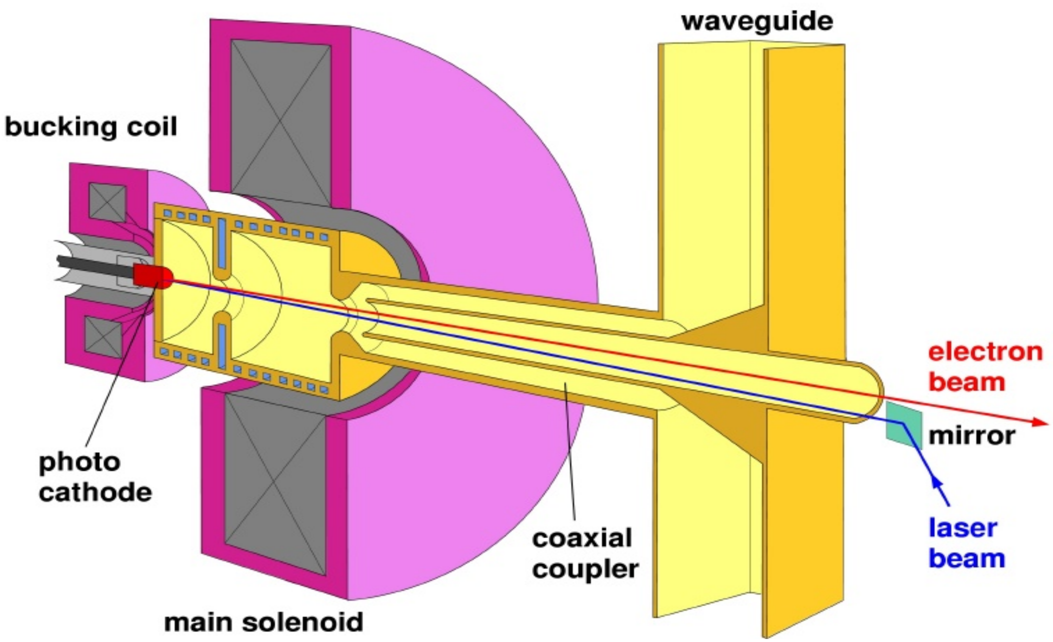


The PITZ electron gun



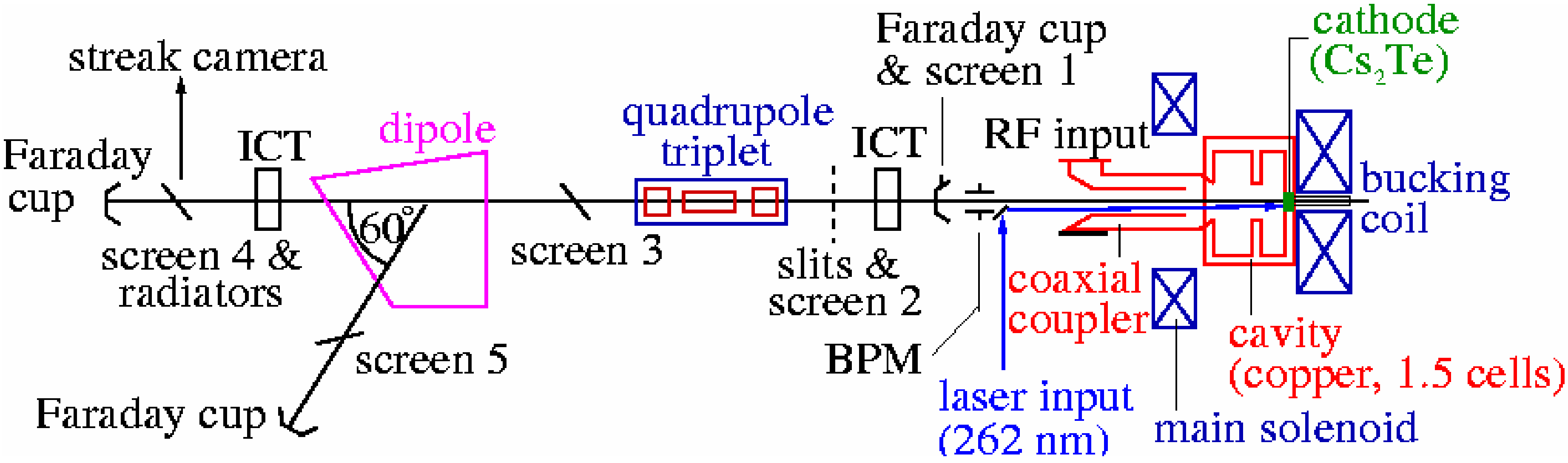
- normal conducting 1.5 cell copper cavity
- frequency: 1.3 GHz (π-mode)
- coaxial RF input coupler
- 3 similar prototypes exist





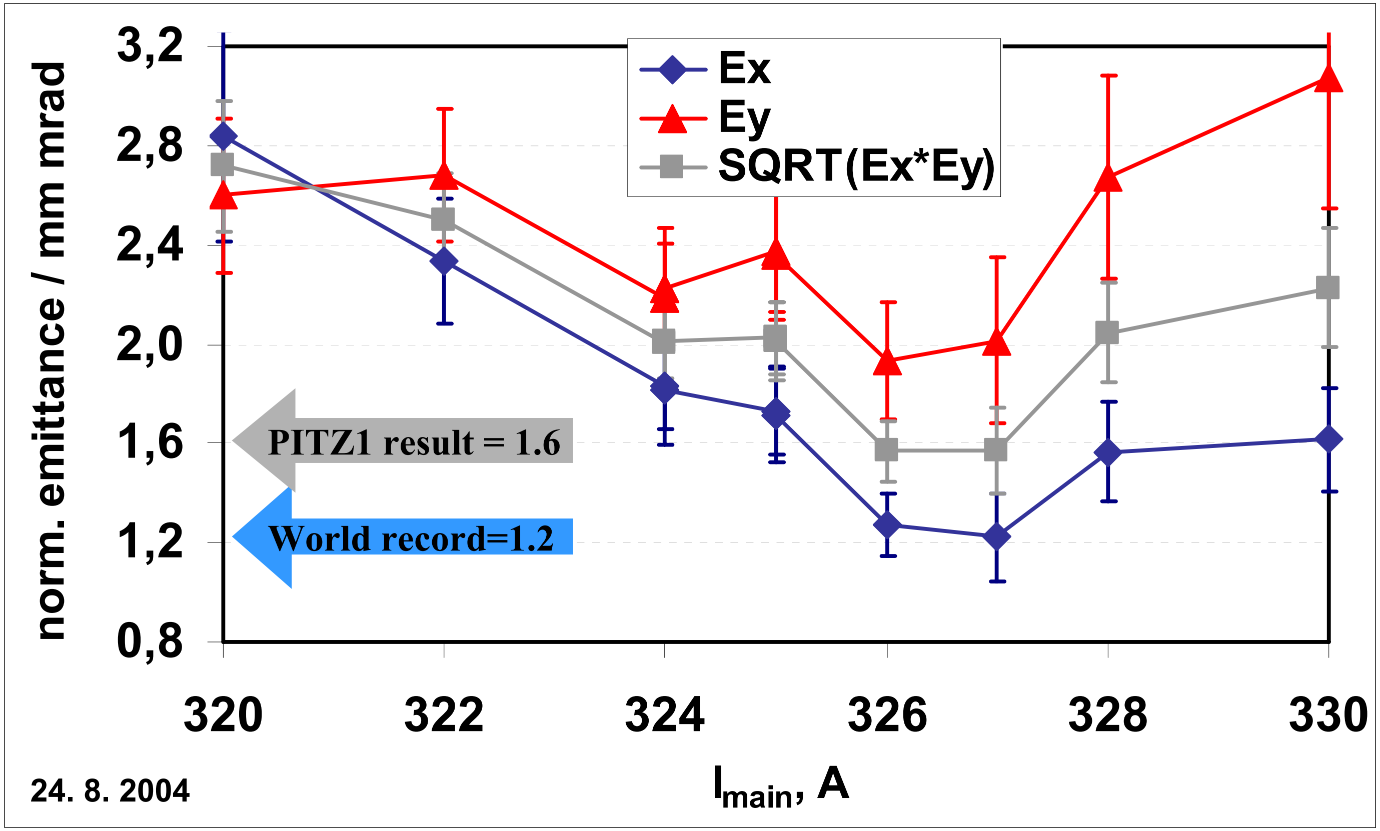
The PITZ1 setup

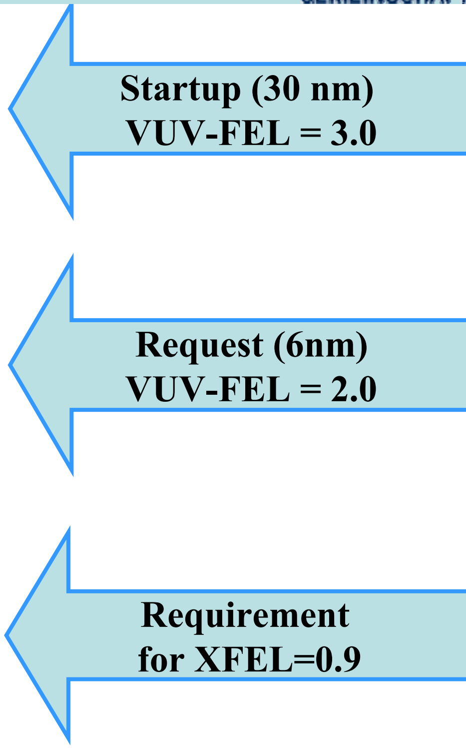
Schematics:



- PITZ1 phase (2001–2004) included the full characterization of the installed gun cavity
- full parameter optimization for emittance minimization has been done
- very good emittances have been obtained ($\varepsilon \sim 1.6$ mm mrad)

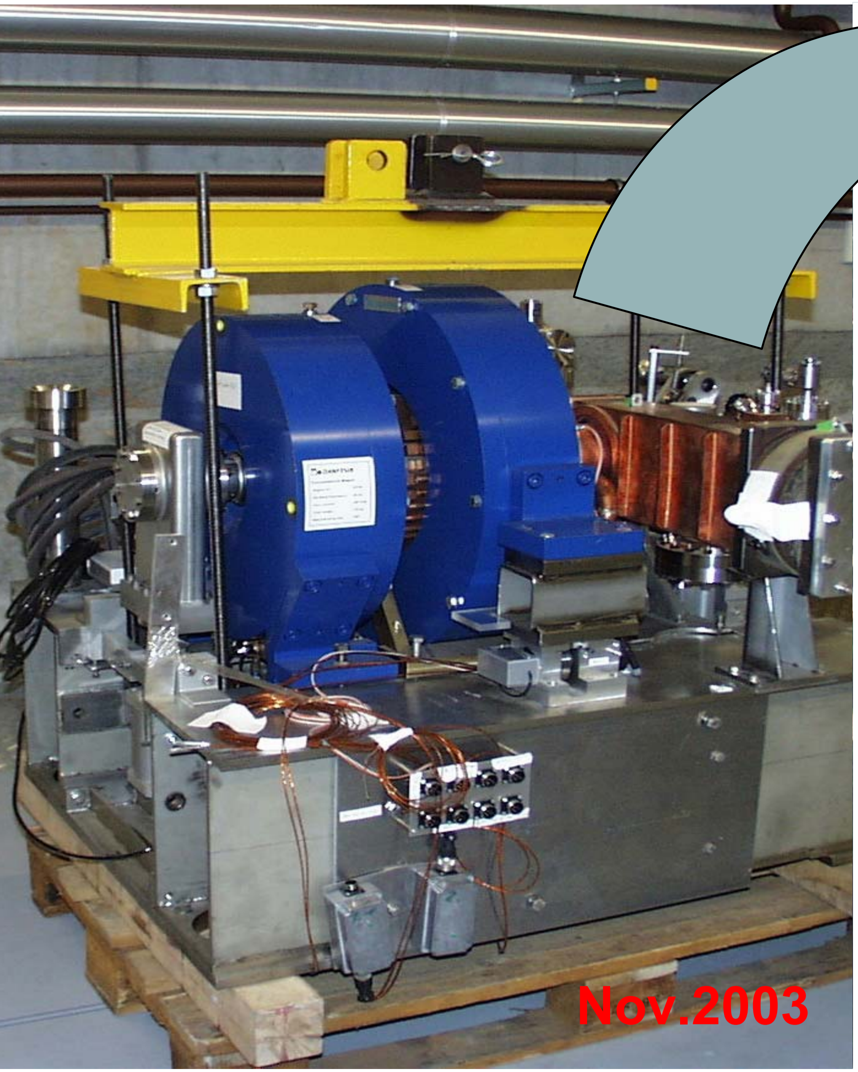
Emittance at PITZ1





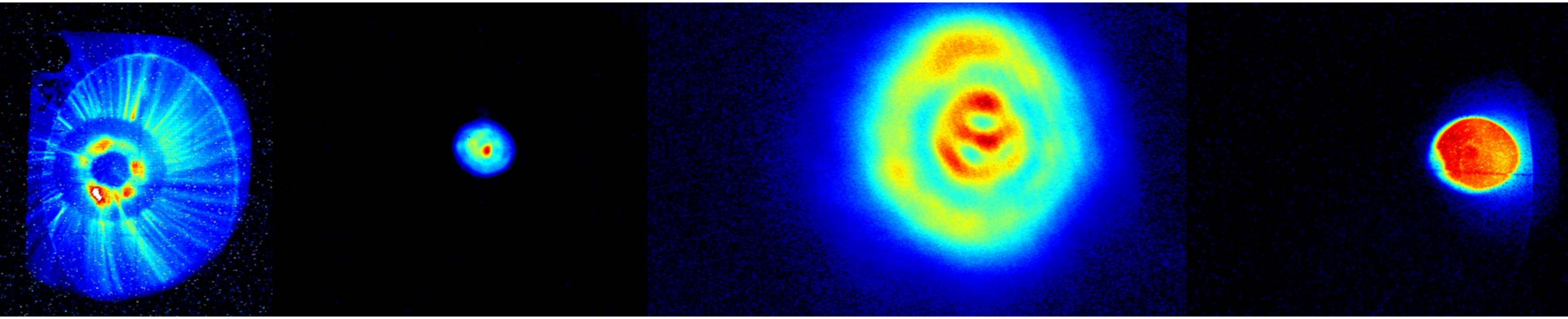
- VUV-FEL startup request clearly fulfilled in 2003
  → gun is transferred to Hamburg and installed in the VUV-FEL
- PITZ continues with a replacement gun

PITZ-gun → VUV-FEL



PITZ1 research program

- Conditioning of the Gun cavity and dark current studies
- The laser system / measurement of laser parameters
- Characterization of the electron beam
  - charge
  - momentum and momentum spread
  - bunch length
  - beam size and transverse emittance
  - thermal emittance



PITZ1 results

- Gun conditioning -

1st Problem: max. acceleration gradient only reachable when full RF power in the cavity

→ condition Gun for all possible RF settings (power level, pulse length, repetition rate) and solenoid magnet currents

→ mainly improve cavity surface

→ field emission (multipacting, sparks) may cause damage of cavity, cathode, coupler, RF window

→ vacuum survey during the conditioning process (interlocks)

2nd Problem: dark current is emitted (mainly from cathode) during the full RF pulse duration

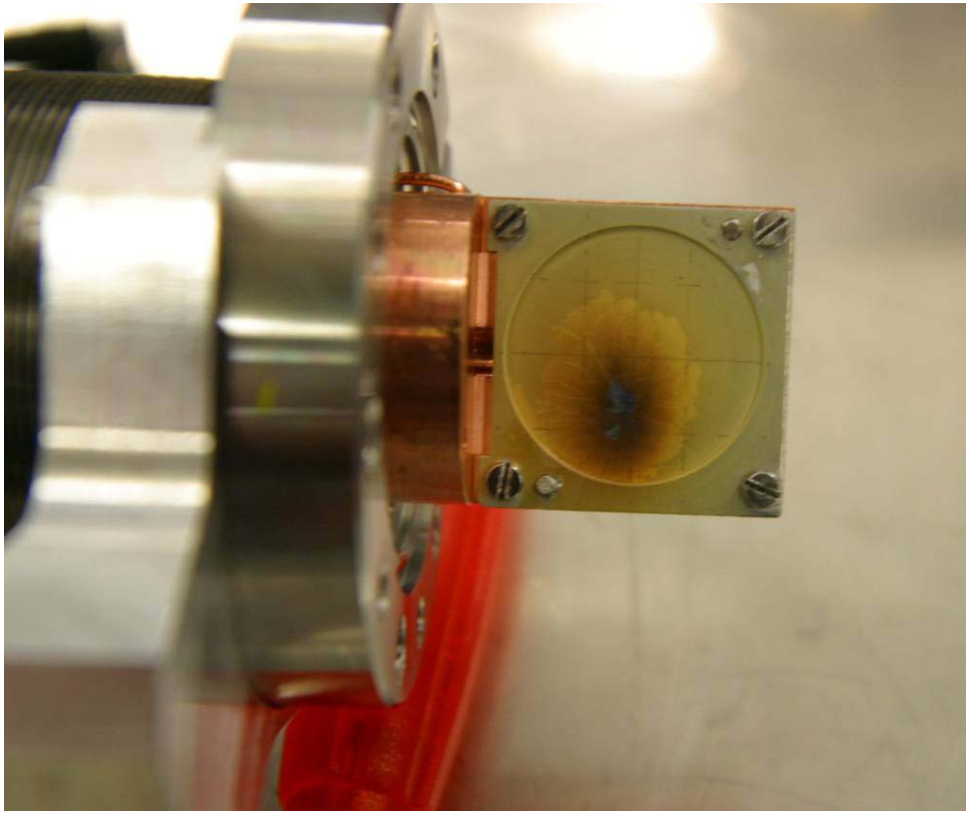
→ large amount at high power levels / long pulses

→ may destroy cathode and diagnostics (e.g. screens)

→ can be transported until the undulator and damage it

PITZ1 results

- Damages due to dark current ? -



We experienced damages on screens and cathodes.

PITZ1 results

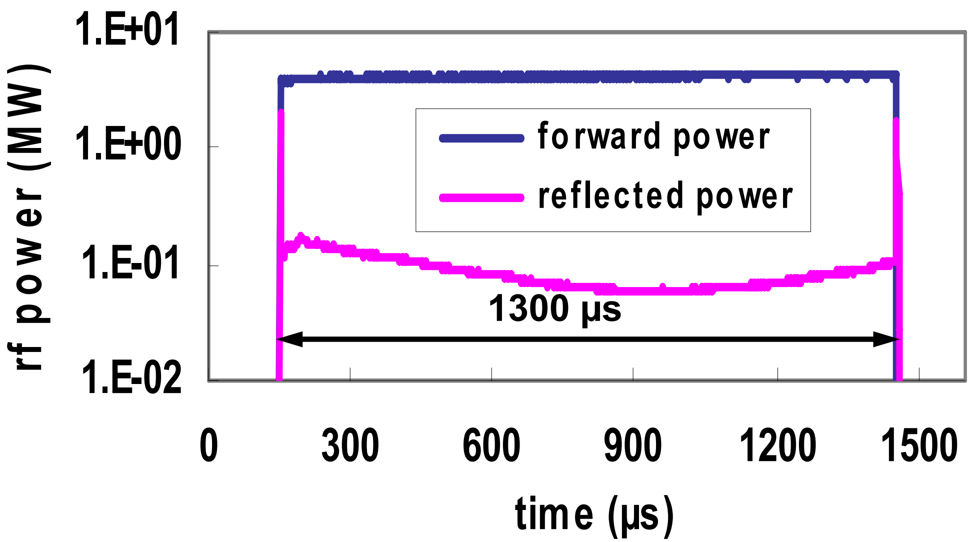
- Gun conditioning -

repetition rate	10 Hz	5 Hz	10 Hz
rf pulse length	0.5 ms	1.3 ms	1.0 ms
peak power at gun	4 MW	4 MW	3 MW
average power	20 kW	26 kW	30 kW
duty cycle	0.5 %	0.65 %	1.0 %

limited by 5 MW klystron and water cooling system

⇩

necessary upgrades:
- 10 MW klystron
- new cooling system



Requirements of VUV-FEL fulfilled

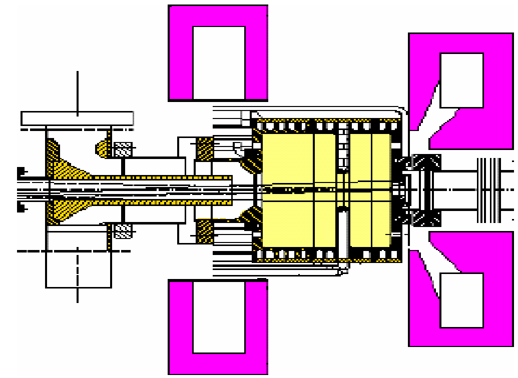
Goal parameters for the XFEL (60 MV/m):
~ 7 MW, ≤ 0.65 ms, 10 Hz

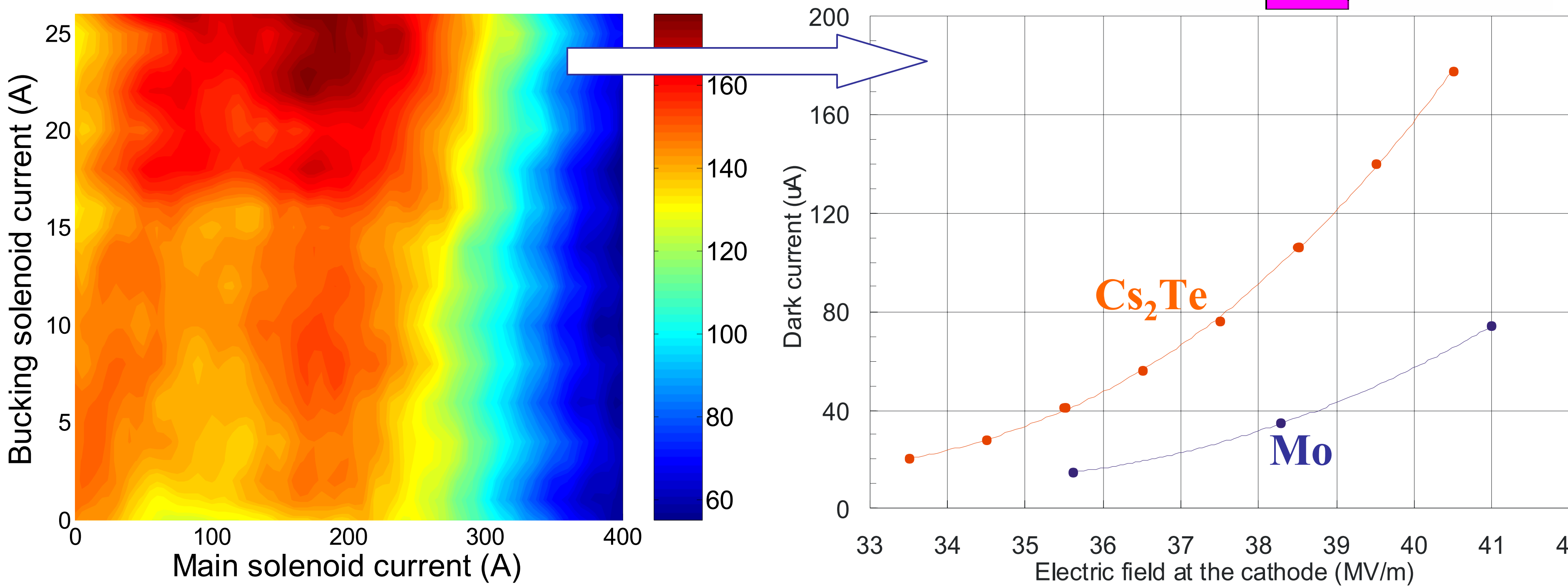
PITZ1 results

- Dark current measurements -

Dark current measurements in dependence on
- accelerating gradient at the cathode
- cathode material (Mo / Cs_2Te)
- solenoid current

and its time development

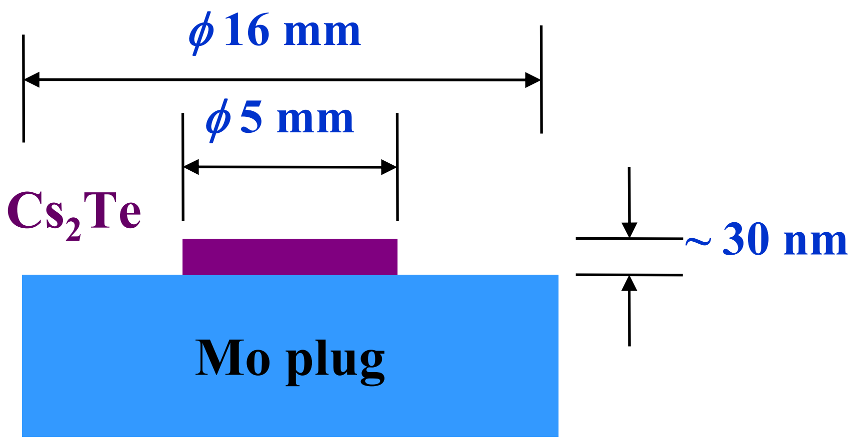


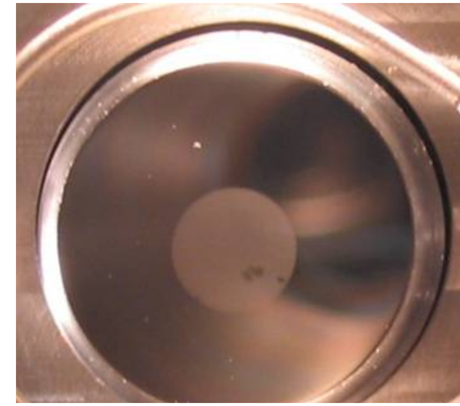


PITZ1 results

- Dark current studies -

side view of the cathode



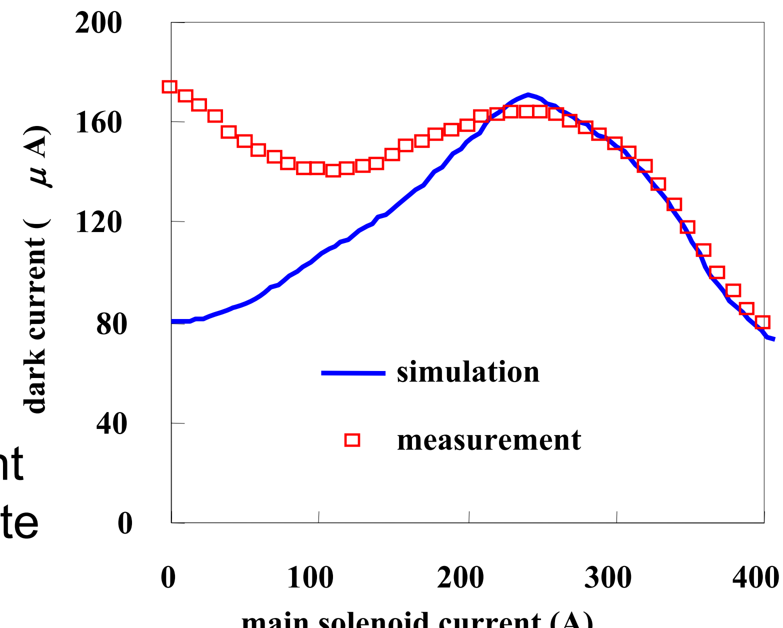


front view of the cathode

Possible dark current sources:

- Cs_2Te film
- edge of Cs_2Te film
- Mo plug
- edge of Mo plug

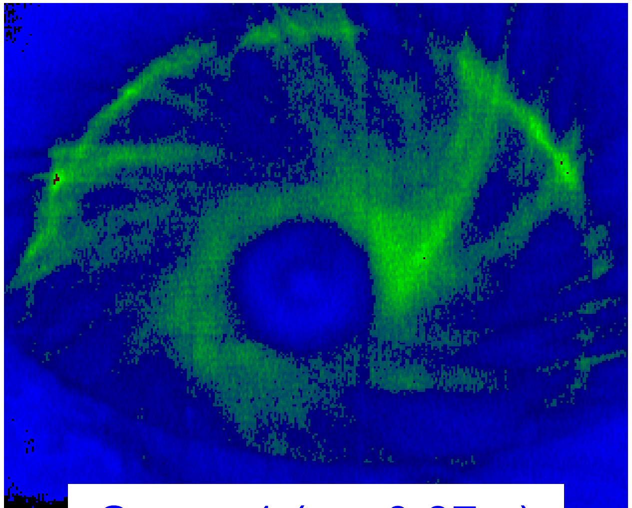
→ field emission model for the cathode



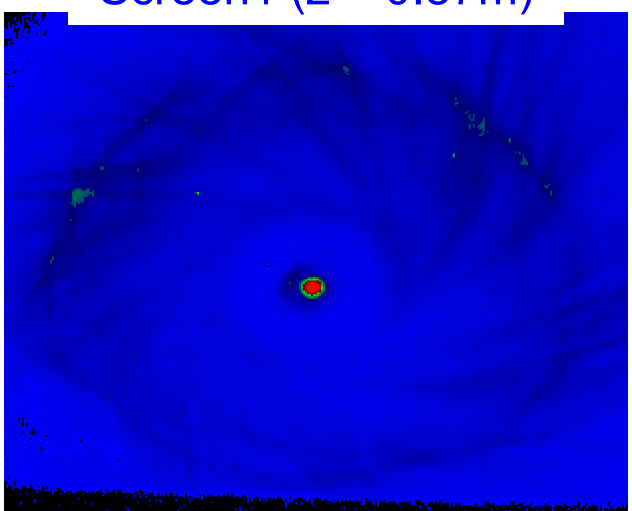
Discrepancy between simulation and measurement
→ additional emission mechanisms could contribute

PITZ1 results

- Dark current studies -



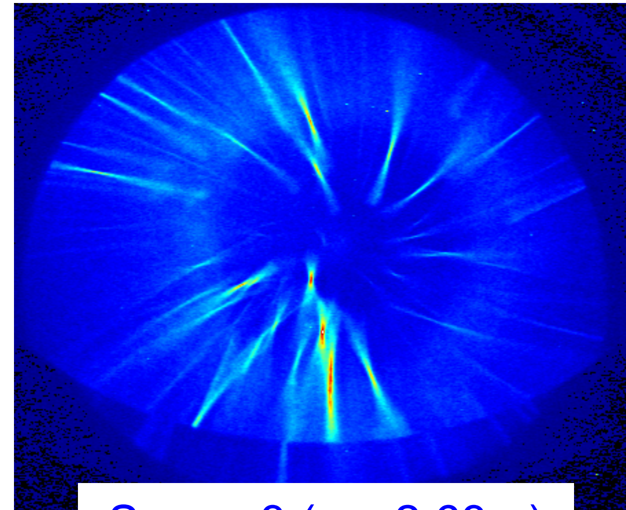
Screen1 (z = 0.87m)



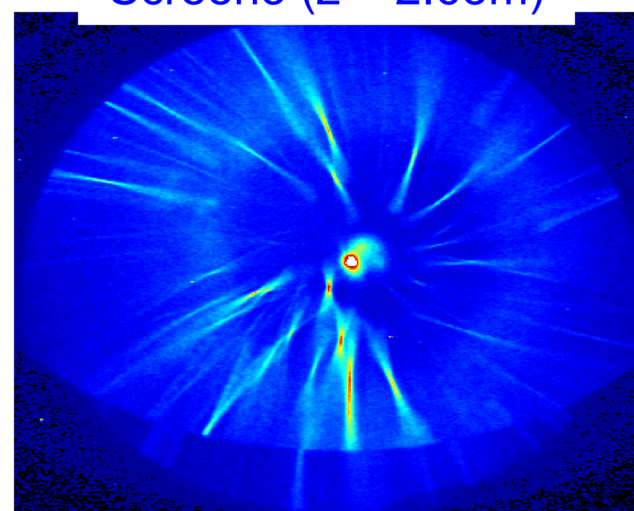
without beam

↕

with beam

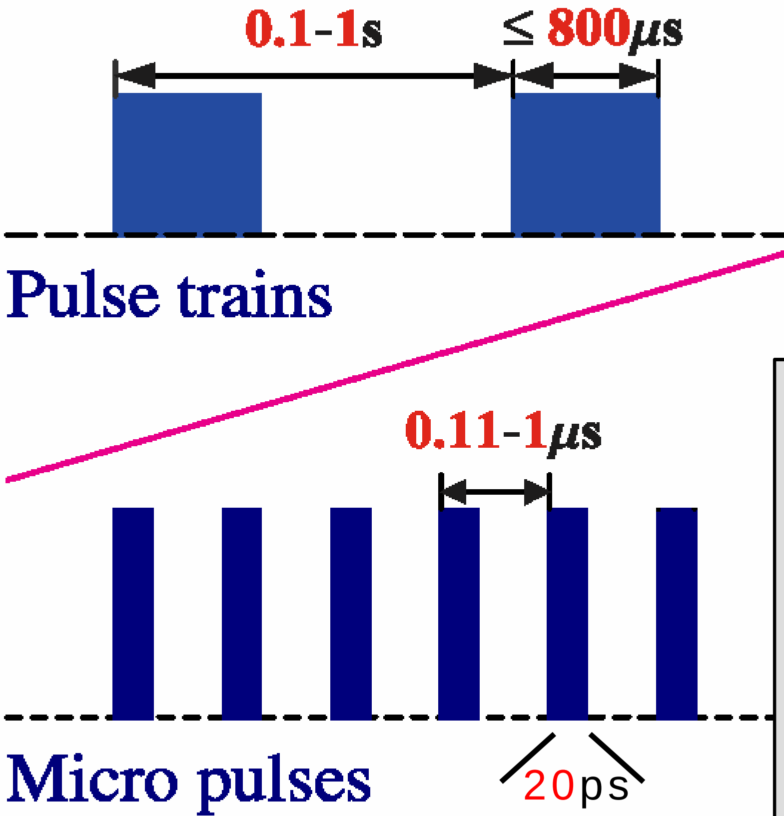


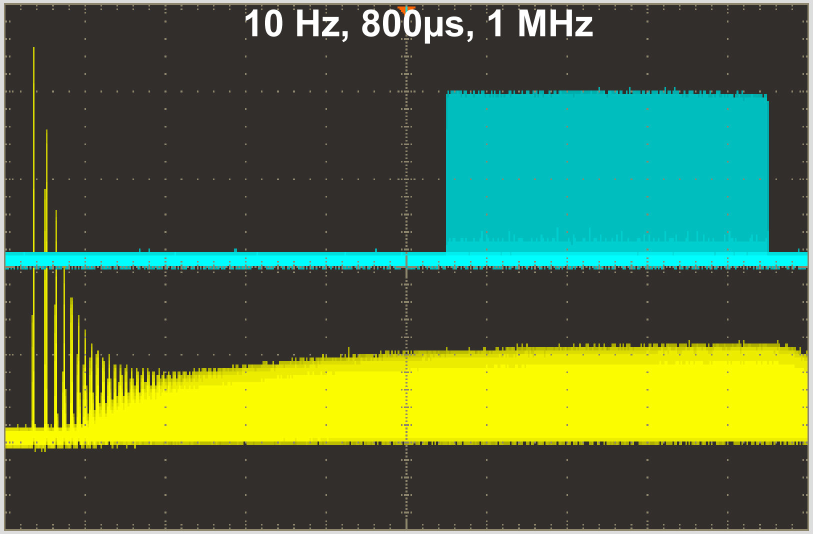
Screen3 (z = 2.63m)



The PITZ laser system

using sc linac technology for VUV-FEL / XFEL → long pulse trains

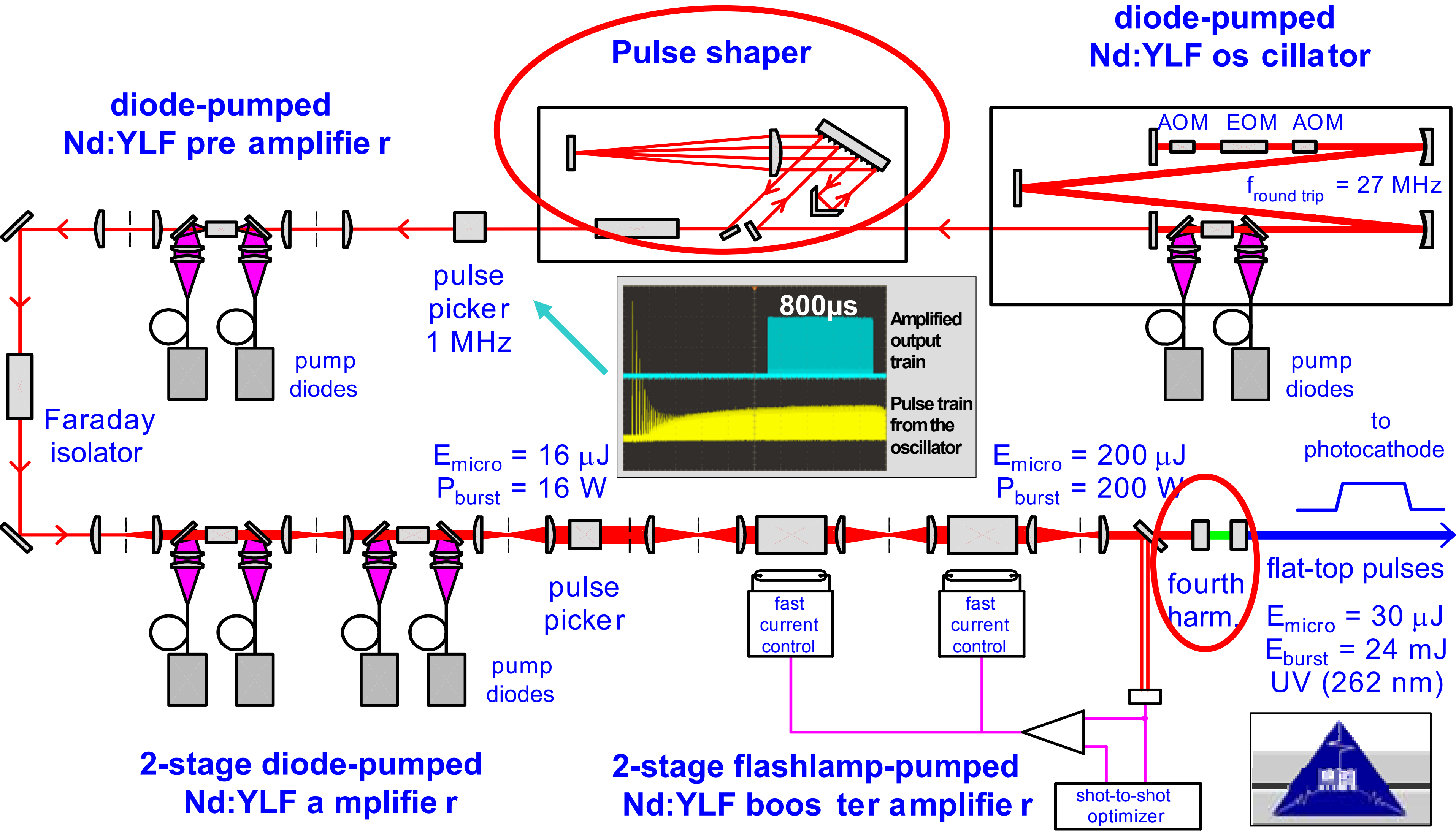




amplified output train

pulse train from the oscillator

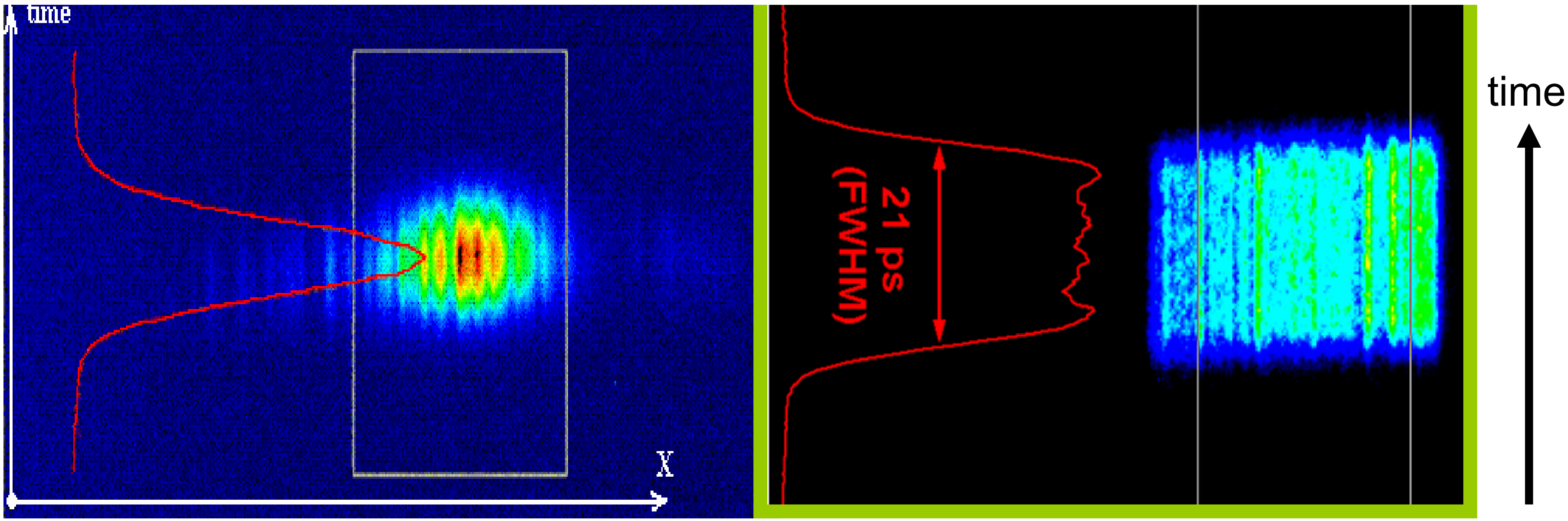
The PITZ laser system



Laser parameters

Longitudinal laser pulse shape can be changed between

gaussian	**and**	**flat-top**
e.g. before 23.6.03 FWHM = 7 ± 1ps		e.g. after 23.6.03 FWHM ≈ 19-23 ps rise / fall time 5-7 ps



Minimum measured emittance:

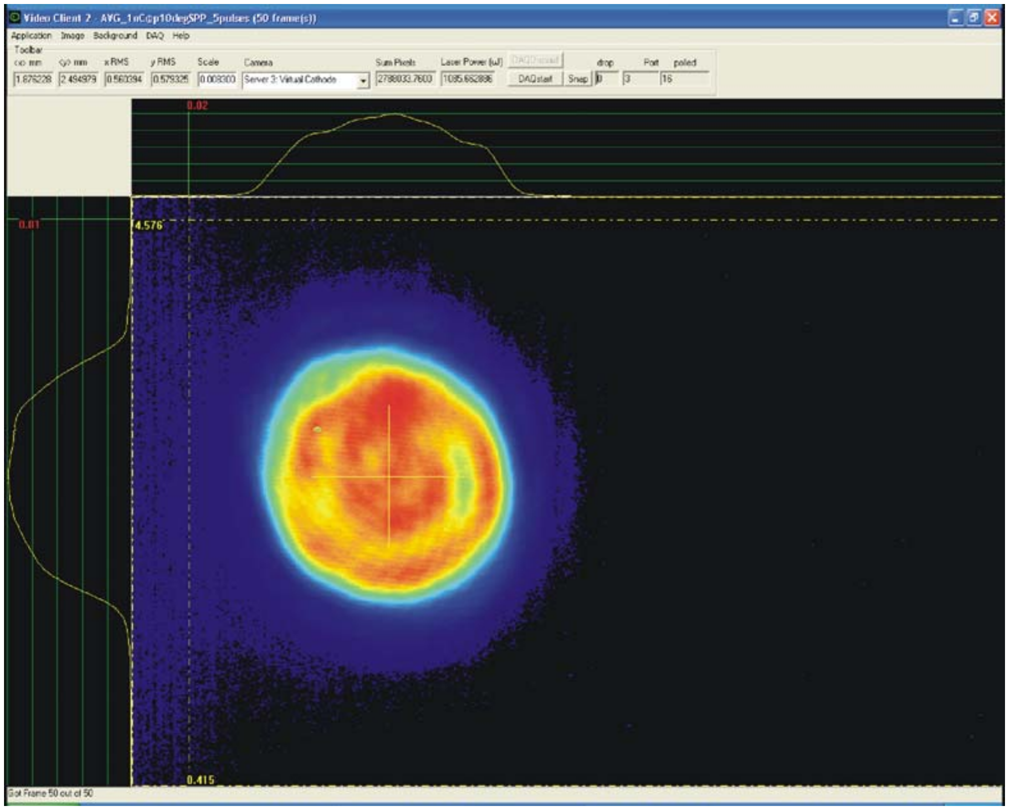
≥ 3 mm mrad	**1.6 mm mrad**

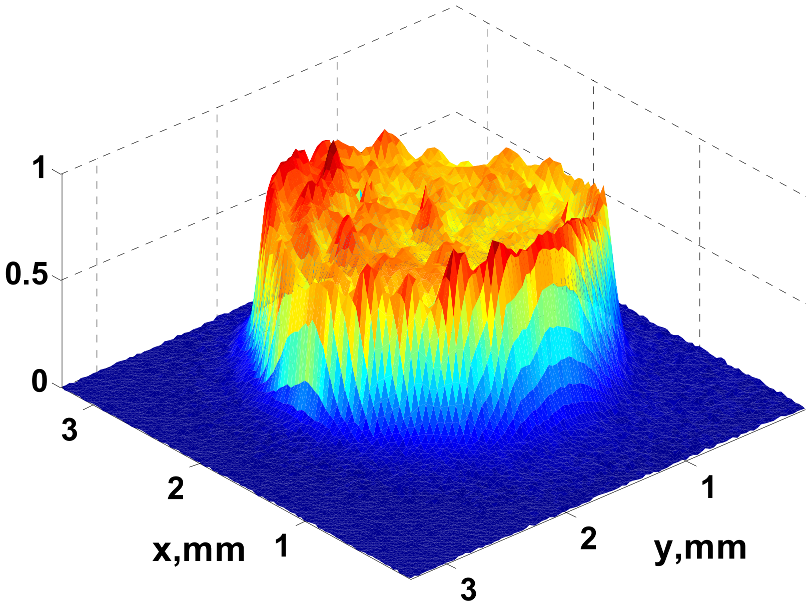
Laser parameters

Transverse laser profile
(pictures from the ‘virtual cathode’)

σ_x = (0.57 ± 0.02) mm

σ_y = (0.58 ± 0.02) mm

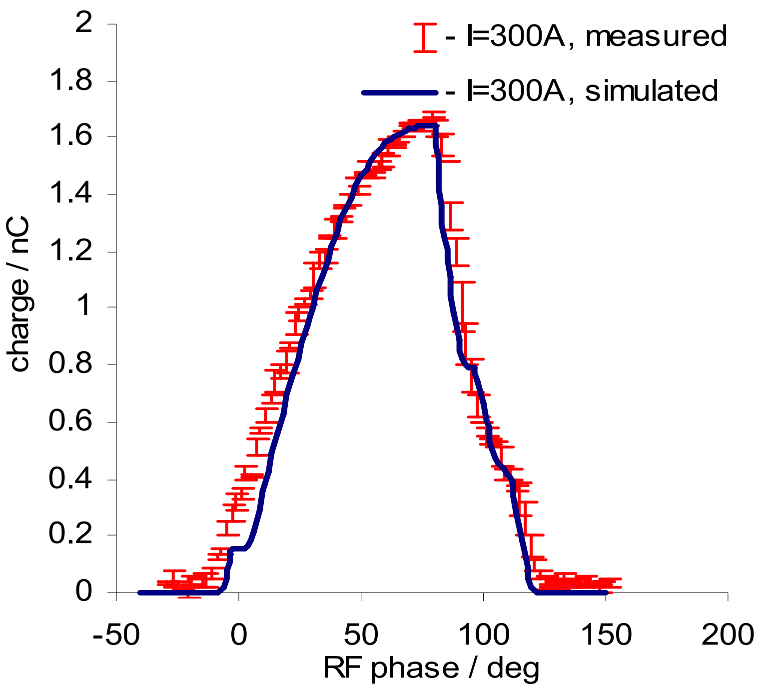


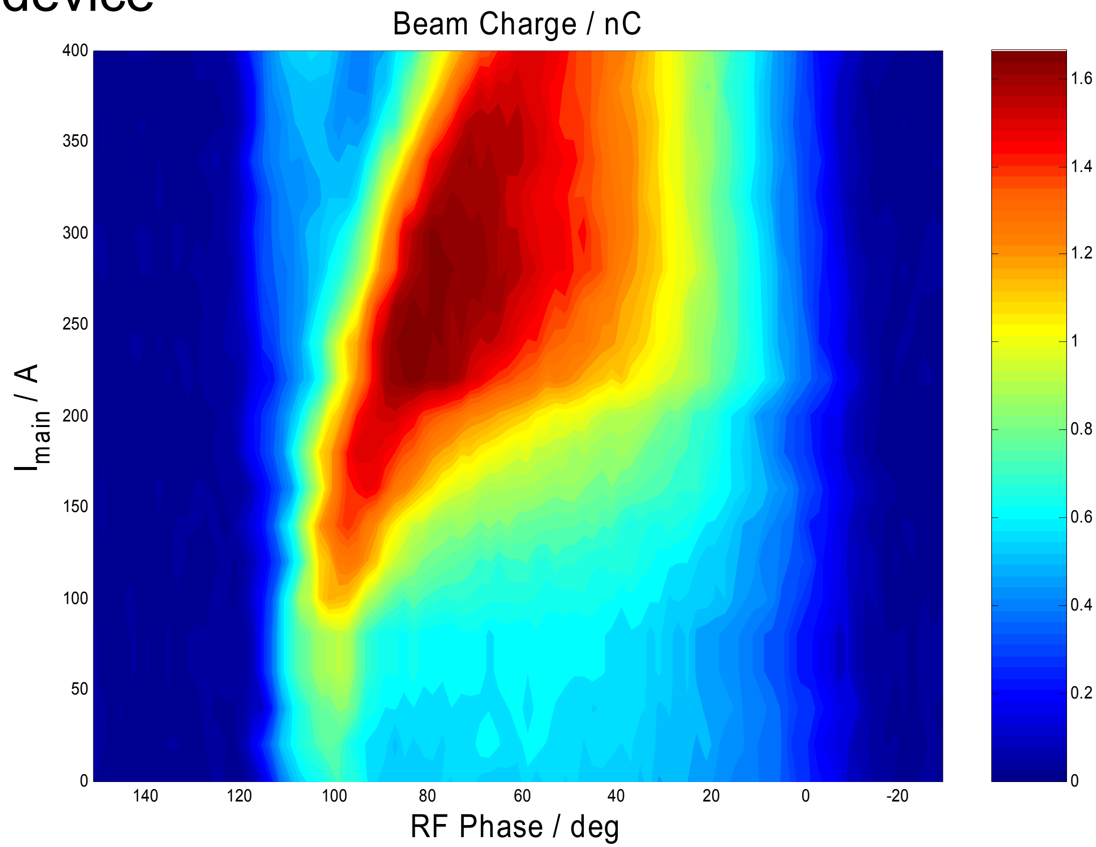


PITZ1 results
- Bunch charge -

- charge measurement with FC or ICT
- measured charge depends on
  - position of measurement device
  - phase of the RF field
  - solenoid current

Nominal charge: 1 nC



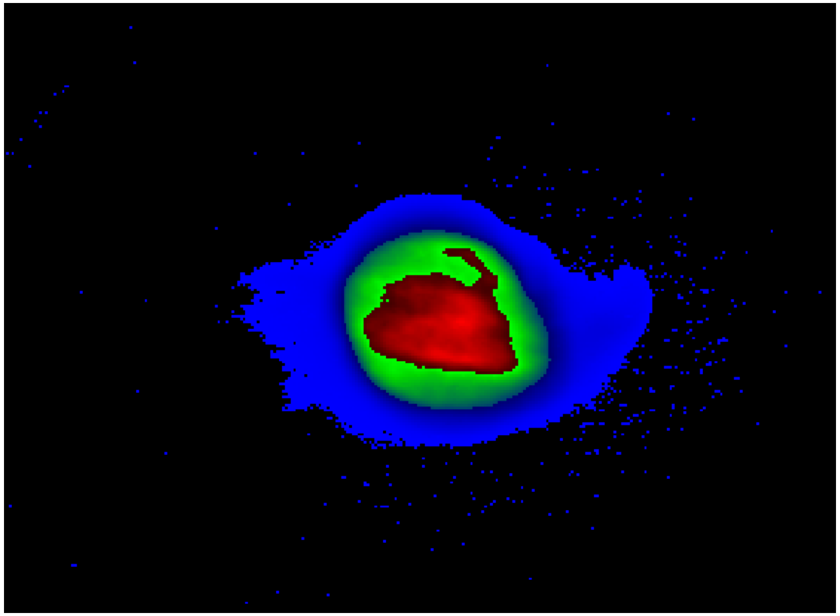


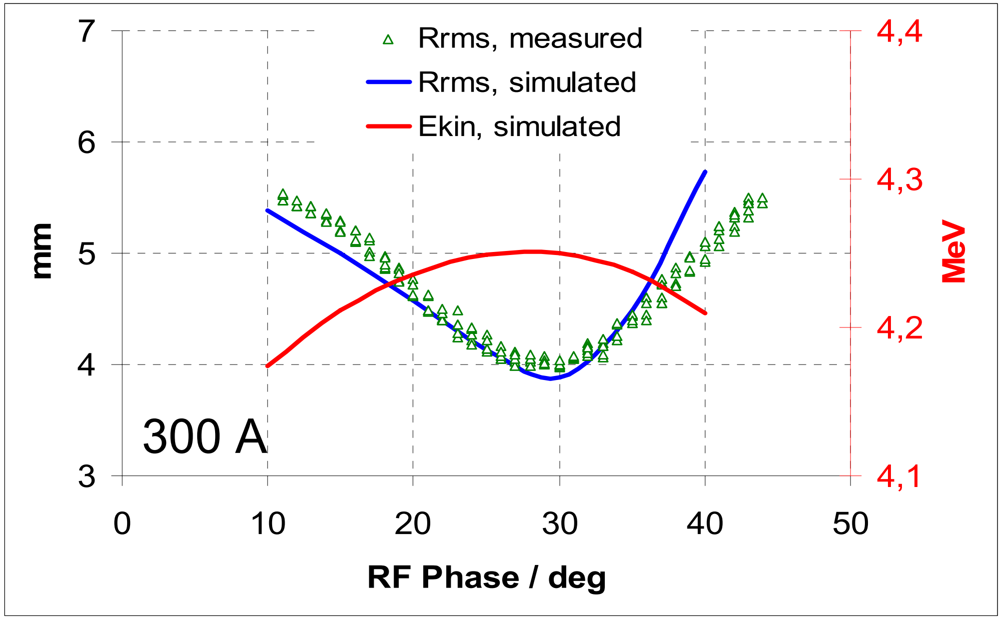
PITZ1 results

- Beam size measurements -

- measured with YAG screen
- study dependence on
  - screen position
  - RF phase
  - solenoid current

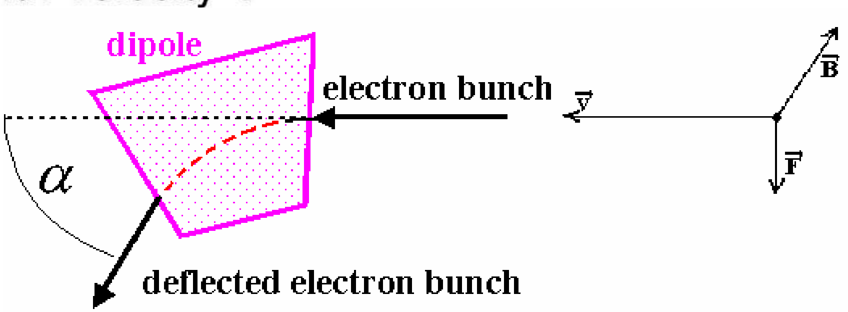
Application:
Determination of the reference phase
(phase of maximum energy gain)
→ measure the electron beam size
as function of the launch phase





Principle of momentum measurement

The Lorentz-Force: Motion of electrons with velocity $\vec{v}$ and mompentum p in magnetic field $\vec{B}$



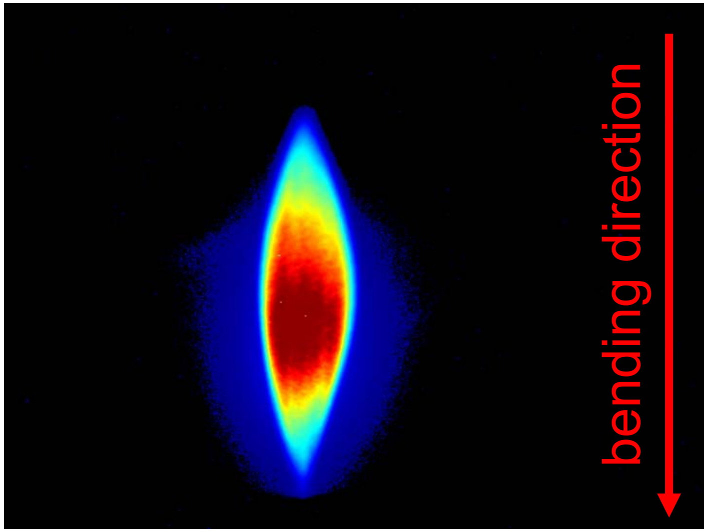
$$\vec{F}_L = e(\vec{E} + \vec{v} \times \vec{B})$$

Magnetic Rigidity:

$$\vec{F}_L = evB = \frac{mv^2}{\rho}$$

ρ : Radius of curvature of the path

$$B\rho = \frac{mv}{e} = \frac{p}{e}$$

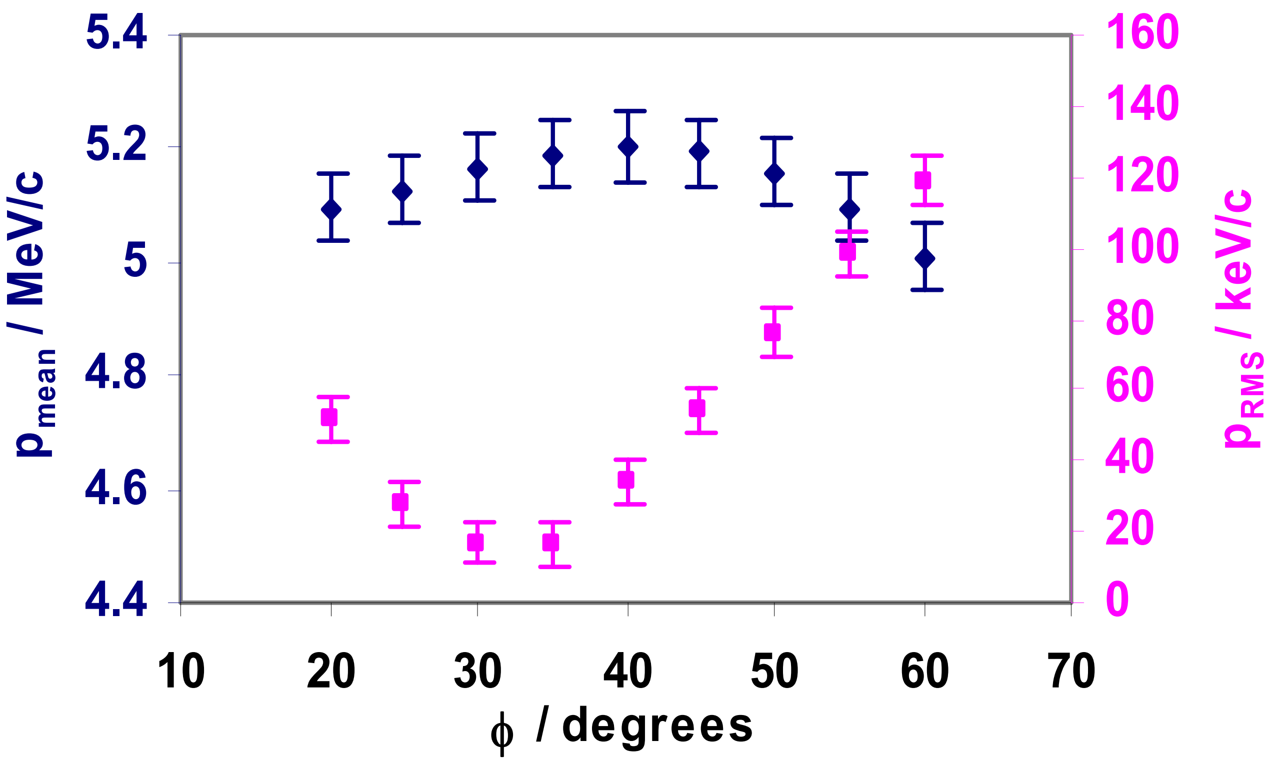


PITZ1 results

- Momentum and momentum spread -

Q = 1 nC

Measurement as function of the RF phase:



max. mean momentum:
5.20 MeV/c

min. rms momentum spread:
16 keV/c

phase difference between p_{mean}^{max} and p_{RMS}^{min}
only ~5 degrees

PITZ1 results

- Bunch length measurements -

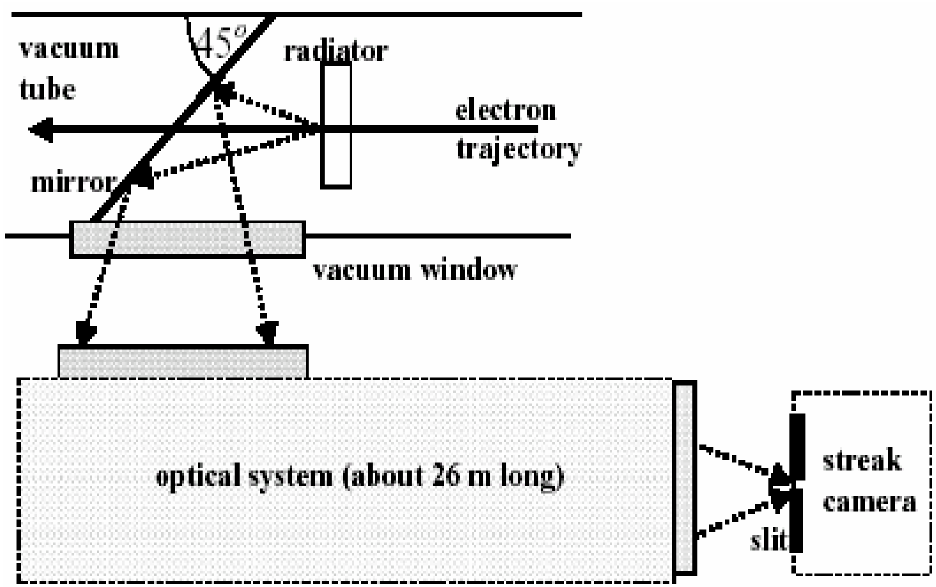
Principle:

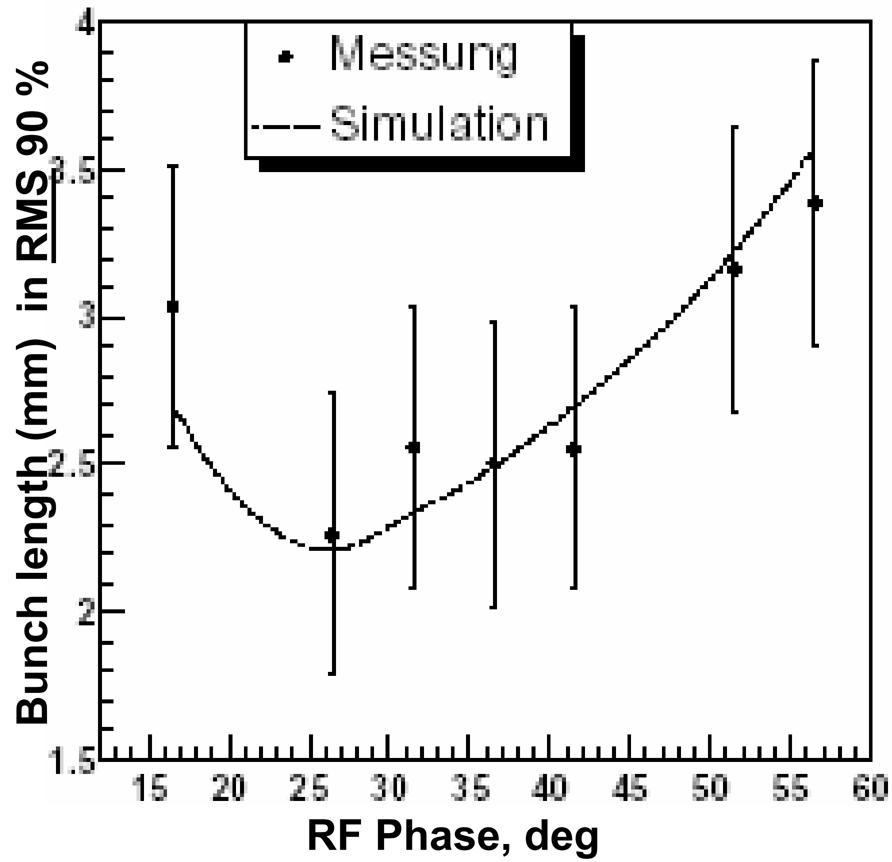
- electron bunch hits radiator (aerogel / quartz) and radiates photons
- analysis of time development with streak camera

Minimum length (FWHM):

(21.04 ± 0.45stat ± 4.14syst) ps

(6.31 ± 0.14stat ± 1.24syst) mm



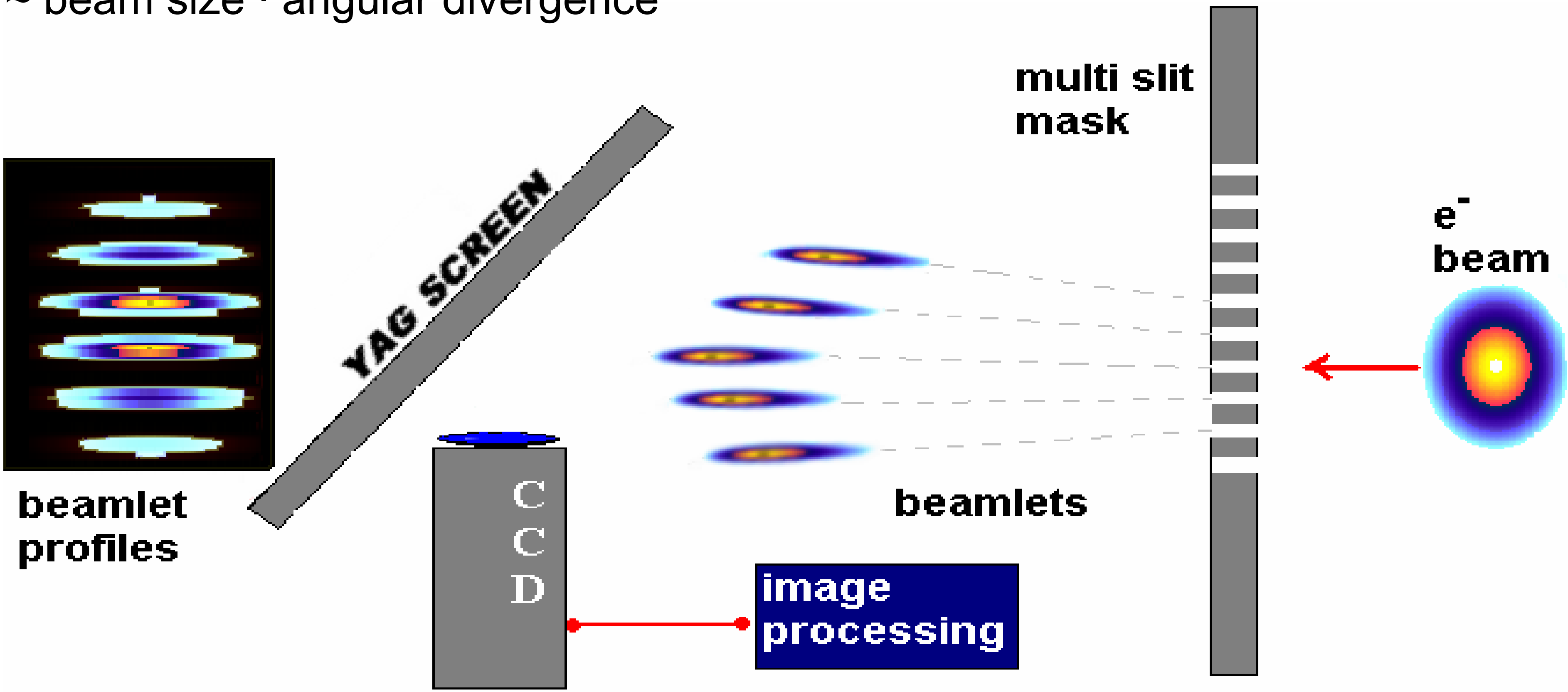


PITZ1 results

- Emittance measurements -

transverse normalized emittance
~ beam size · angular divergence

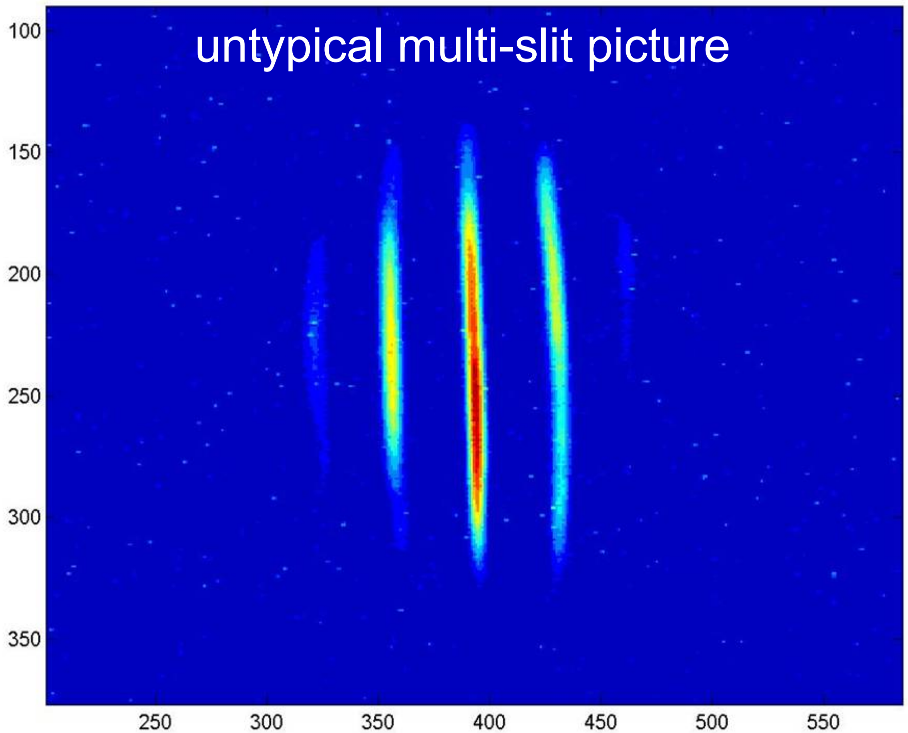
$$\varepsilon_n^2 = \langle x^2 \rangle \langle x'^2 \rangle - \langle x \; x' \rangle^2$$



phase space reconstruction = approximation of real phase space

PITZ1 results

- Emittance measurements -



Problems with multi-slit measurements:

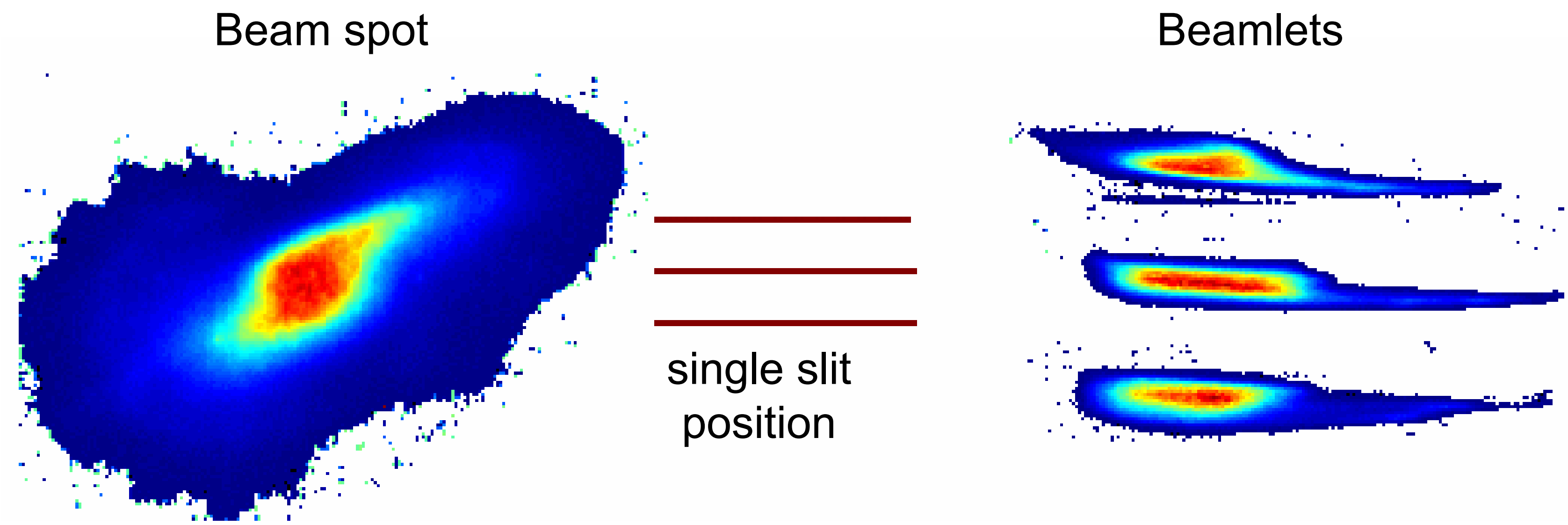
- overlapping beamlets (large divergence)
- only few beamlets (small beam size)

→ not used at PITZ

PITZ1 results

- Emittance measurements -

Single-slit scan technique



The size of the beamlet is measured for three slit positions:

$$y_n = \langle Y \rangle + n \cdot 0.7 \sigma_y$$
$$n \in \{-1, 0, 1\}$$

PITZ1 results

- Emittance measurements -

Simulated emittance for optimum parameters

Charge: 1 nC

Max. gradient: 42 MV/m

Longitudinal laser profile:

– flat top

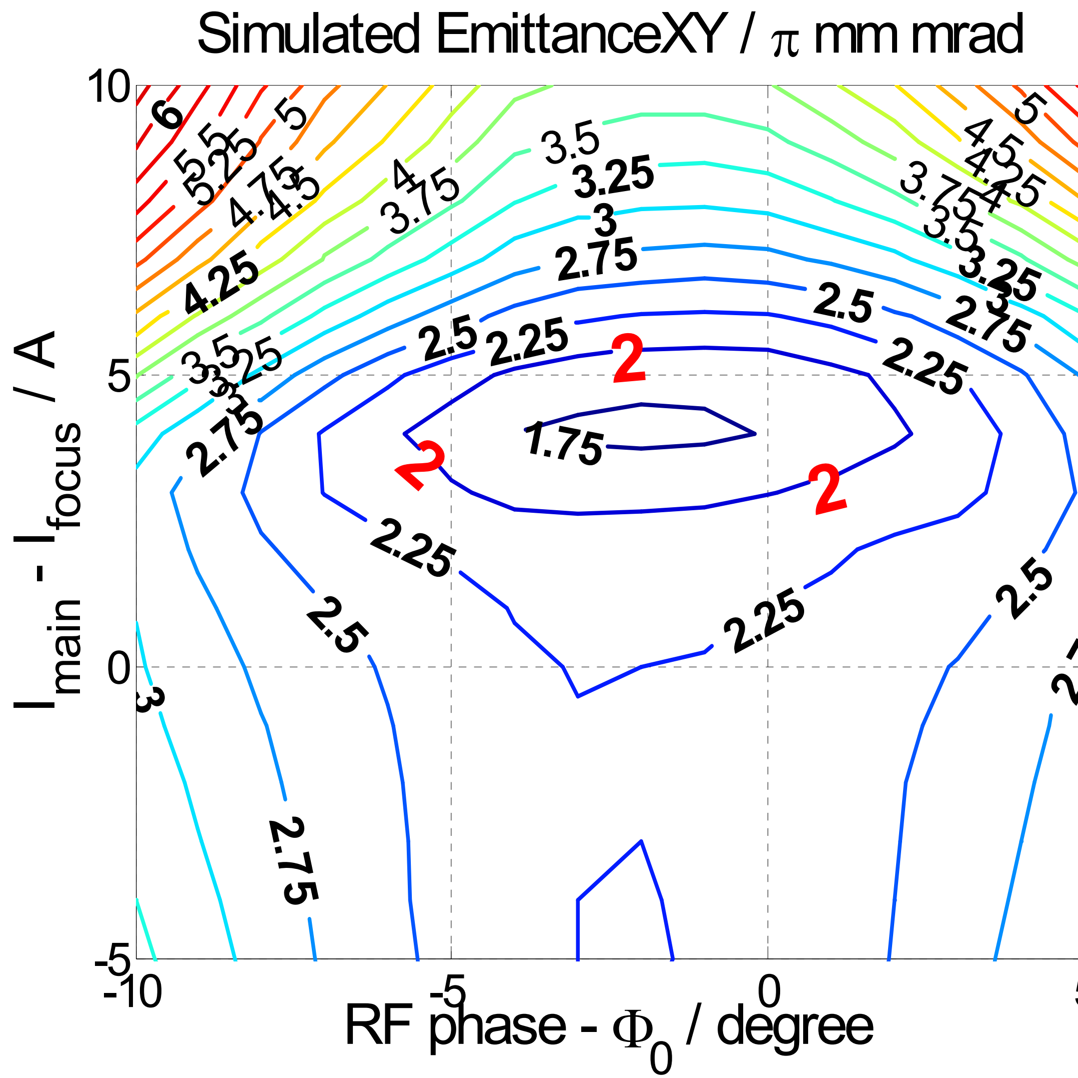
– 20 ps FWHM

– 5 ps rise/fall time

Transverse laser profile:

– homogeneous

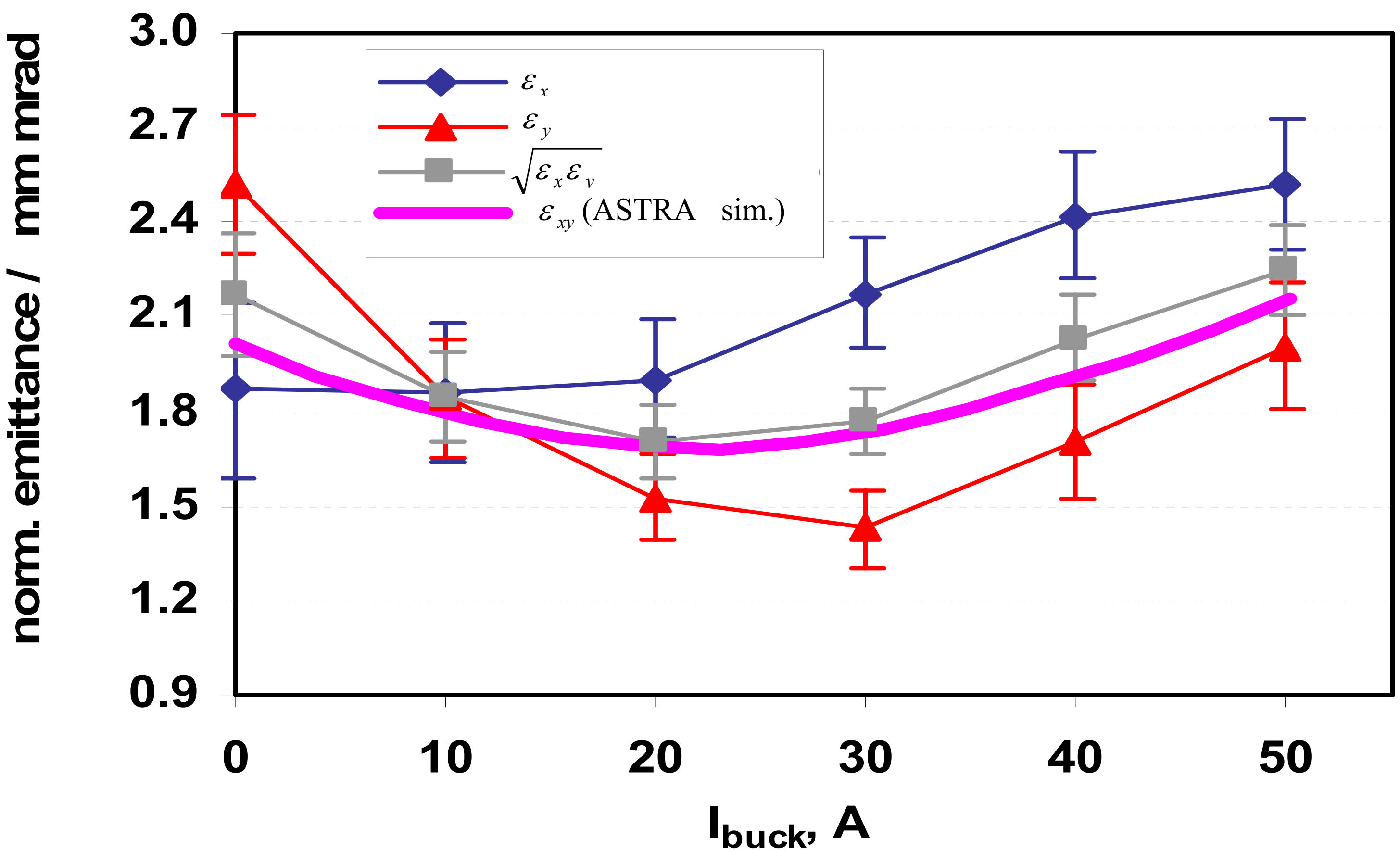
– $\sigma_{x,y}$ = 0.6 mm

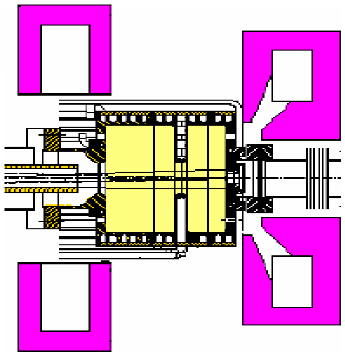


PITZ1 results

- Measured emittance -

e.g. measured transverse emittance as function of the current in the compensating magnet





Q = 1 nC

$\Phi = \Phi_0 - 5°$

Imain = 305A

PITZ1 results

- Thermal emittance -

$$\varepsilon_{th} = \sigma \sqrt{\frac{2E_k}{3m_0c^2}}$$

average kinetic energy of the emitted photo electrons

laser spot size

- thermal emittance adds in quadrature to the other emittance contributions:

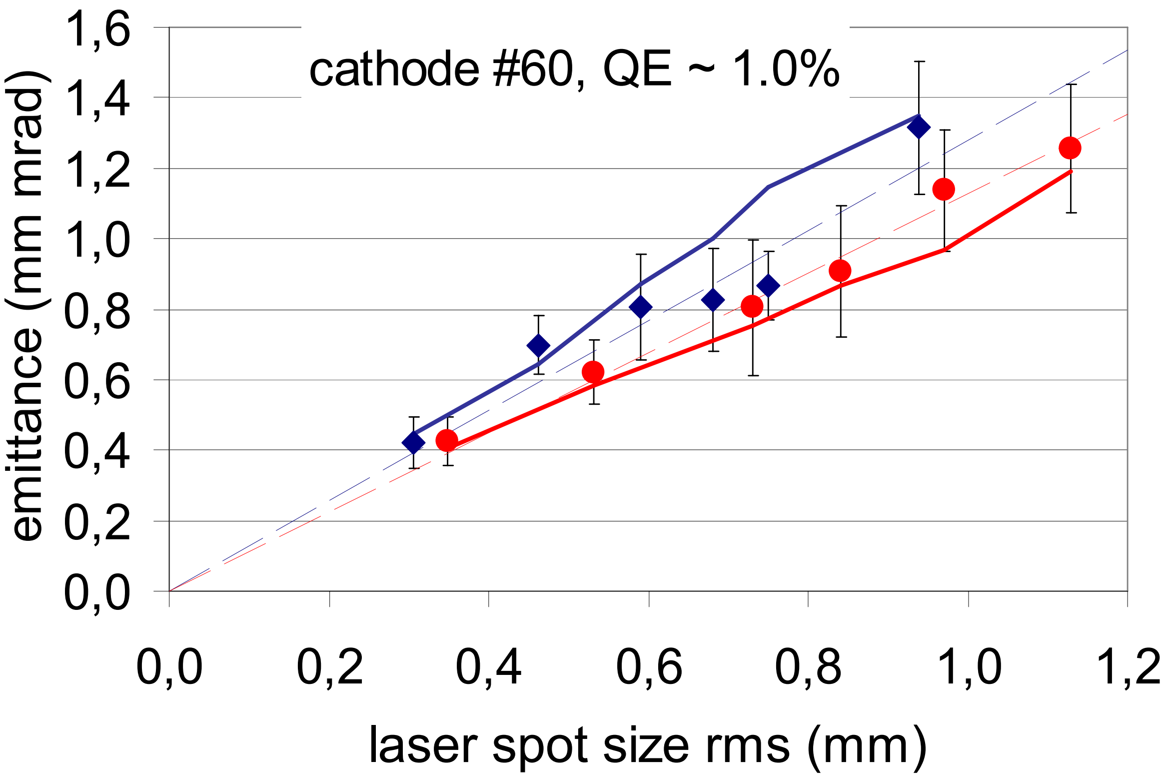
$$\varepsilon_n \approx (\varepsilon^2_{th} + \varepsilon^2_{rf} + \varepsilon^2_{sc})^{1/2}$$

→ thermal emittance sets the lower emittance limit of an electron source

- define operation conditions such that $\varepsilon_{rf} << \varepsilon_{th}$ and $\varepsilon_{sc} << \varepsilon_{th}$:
  Q~2-3 pC, σ_t=3 ps, E_0 < 34 MV/m, laser spot size: 0.48 - 0.55 mm

PITZ1 results

- Thermal emittance -



Kinetic energy of the emitted electrons:

Cathode #60:
(QE ~ 1%)

$$E_k = (1.1 \pm 0.2)\,\mathrm{eV}$$

Cathode #61:
(QE ~ 1.5%)

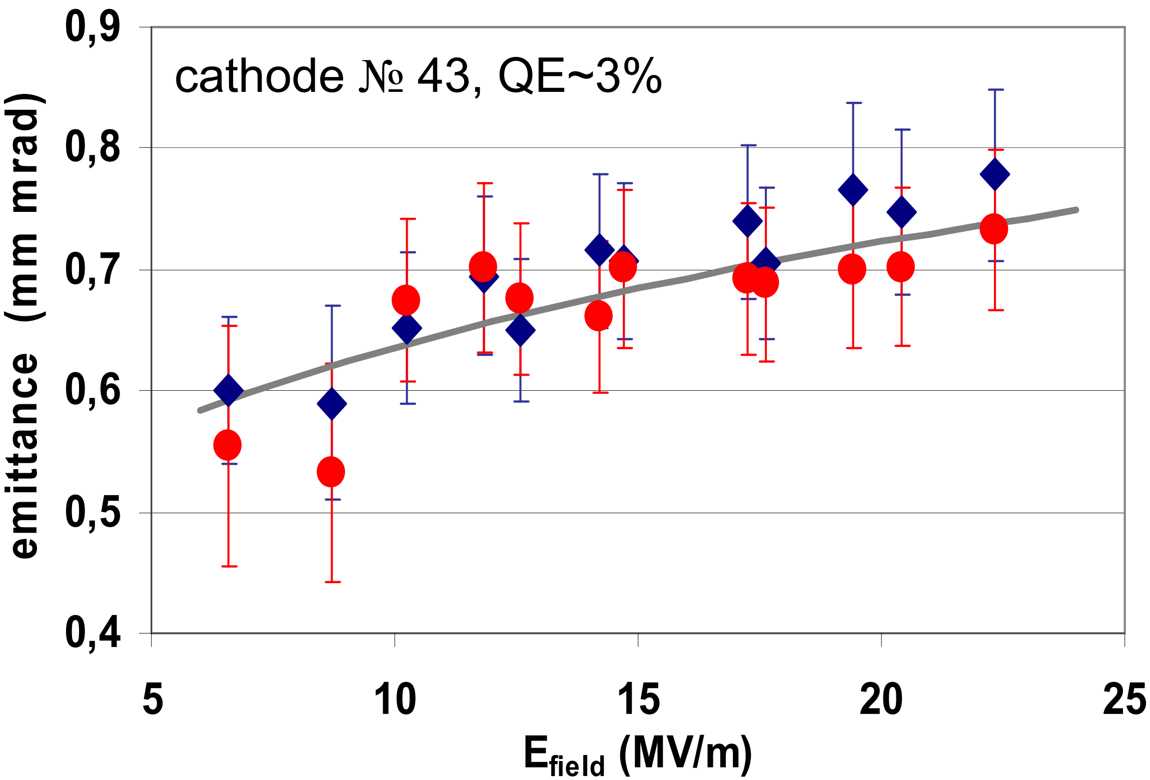
$$E_k = (0.9 \pm 0.2)\,\mathrm{eV}$$

- thermal emittance is individual for each photocathode
- depends on gun operation history and cathode surface chemistry: $\varepsilon_{th} = \varepsilon_{th}(t)$
- more cathode studies are needed (INFN-LASA)

PITZ1 results

- Thermal emittance -

Impact of the electric rf field



Assuming emittance growth due to Schottky effect:

$$\varepsilon_{th} = \sqrt{A + B\sqrt{E_{field}}}$$

Cathode #43:
(Nov.2004, QE ~ 3%)

$$\varepsilon_{\#43} = \sqrt{0.08 + 0.11\sqrt{E}}$$

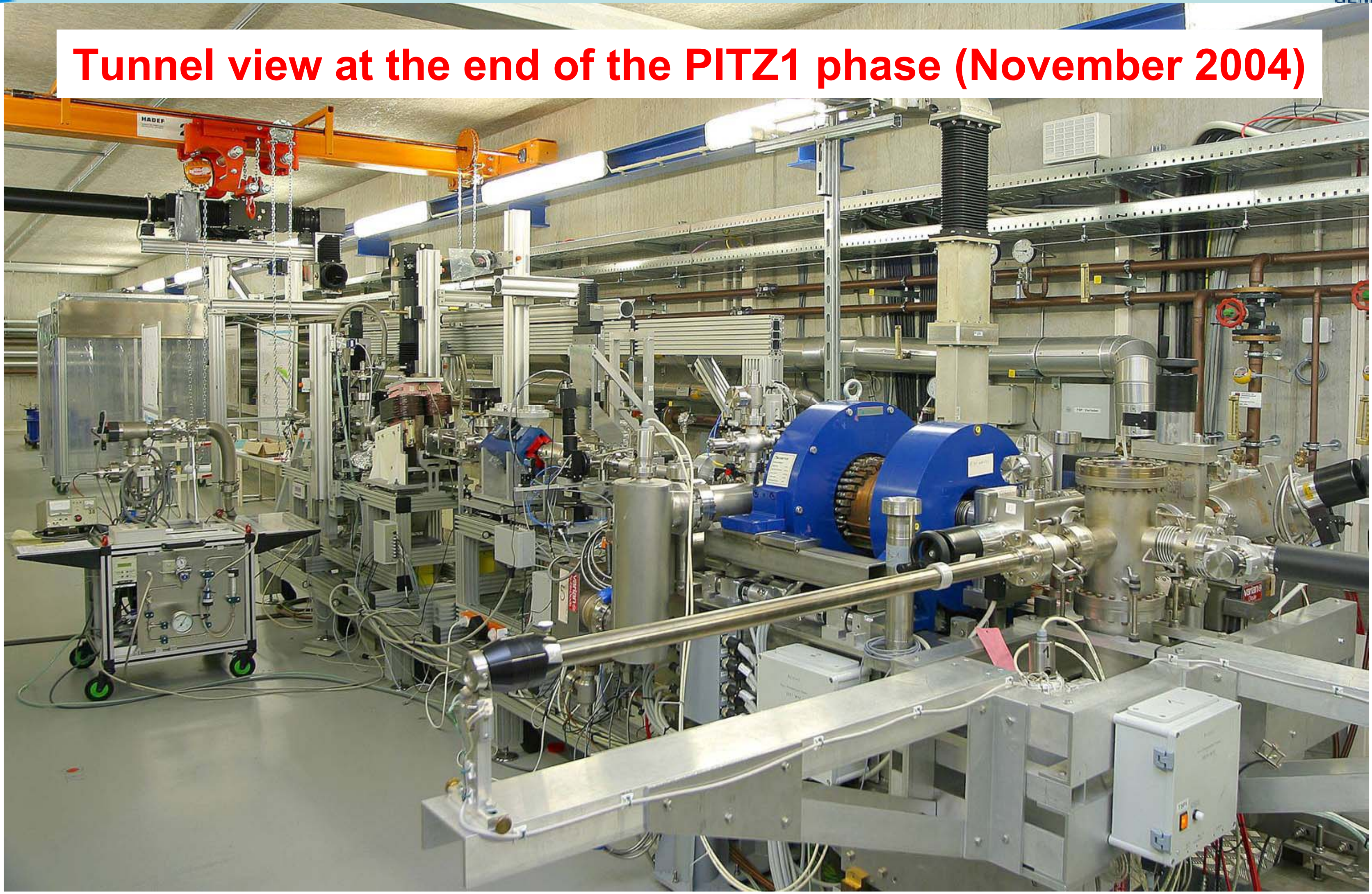
Cathode #61:
(Apr.2004, QE ~ 1%)

$$\varepsilon_{\#61} = \sqrt{0.01 + 0.05\sqrt{E}}$$

Extrapolation for the XFEL case:
(emittance budget: 0.9 mm mrad)

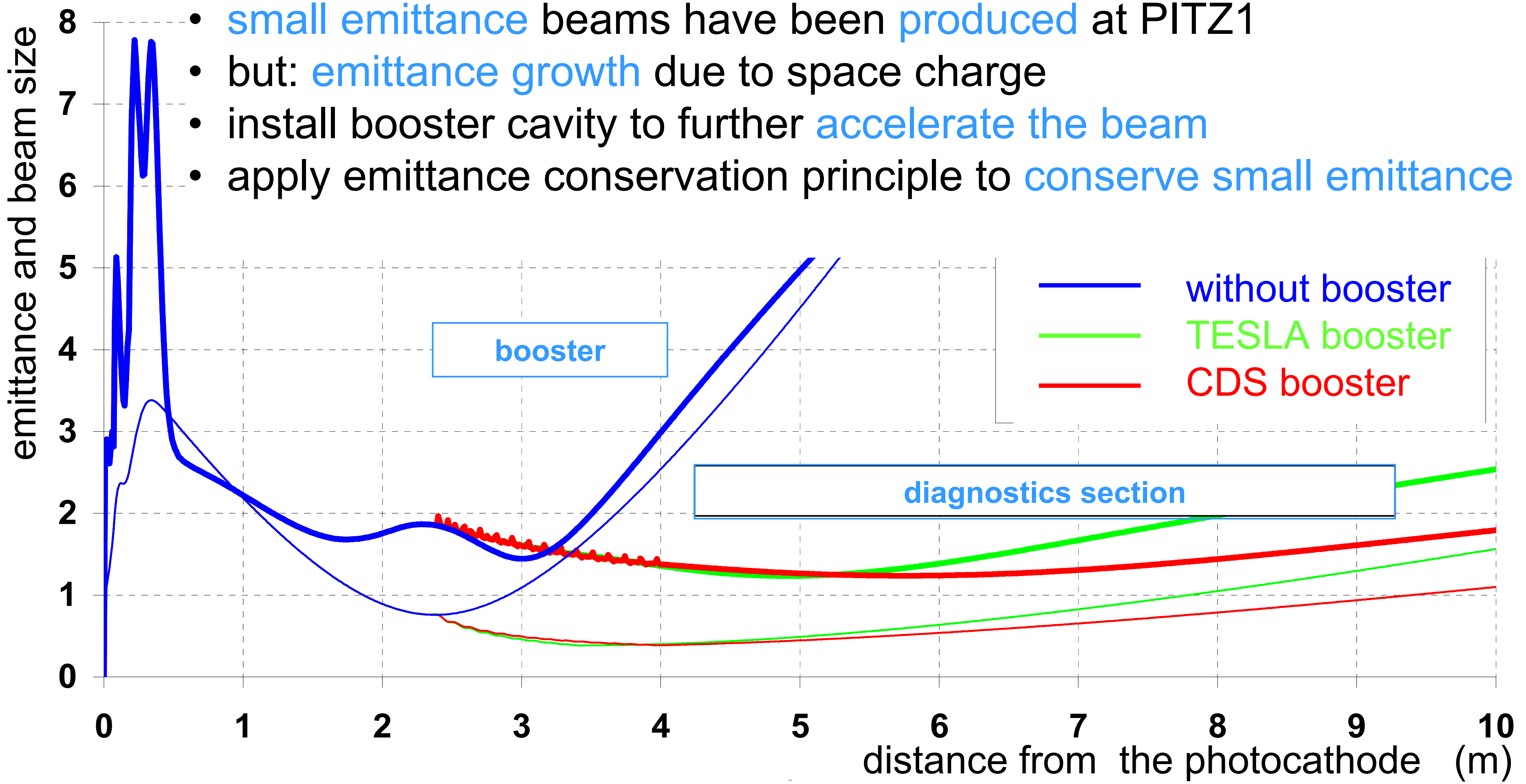
$$\varepsilon = \frac{\sigma_x}{\sigma_y}\sqrt{A + B\sqrt{E_{field}}} \approx 0.7\ mm\ \ mrad$$

The PITZ1 setup



Facility upgrade
- Towards PITZ2 -

- small emittance beams have been produced at PITZ1
- but: emittance growth due to space charge
- install booster cavity to further accelerate the beam
- apply emittance conservation principle to conserve small emittance



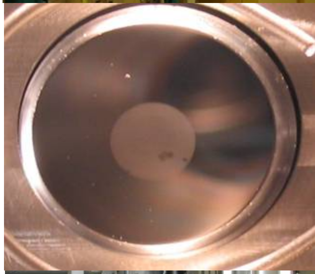
PITZ2 research program

PITZ2 – a large extension of the facility and its research program

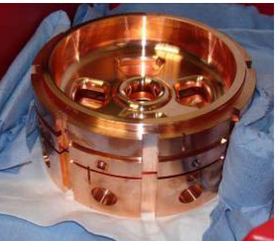
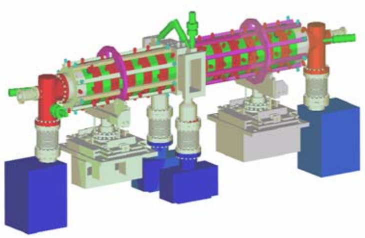
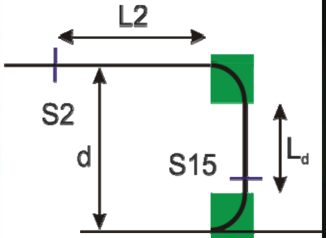
- **study the emittance conservation principle:**
  install booster and new diagnostics beamline
- **benchmark theoretical understanding of photoinjectors:**
  improved simulation tools, detailed comparison simulation vs. measurement
- **reach XFEL requirements (0.9 mm mrad @ 1 nC):**
  increase RF field at the cathode, improve laser system and photocathodes
- **study XFEL parameter space:**
  low charge, short bunches, higher repetition rates
- **test new developments:**
  RF system, gun cavities, diagnostics, cathodes, laser

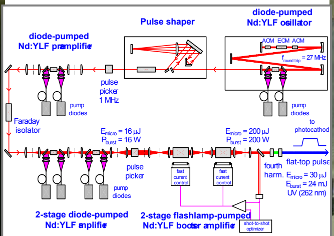
Collaboration partners

- **BESSY Berlin: ICTs, magnets, PS, vacuum expert**
- **CCLRC Daresbury: phase space tomography module**
- **DESY Hamburg: new cavities (Gun3, Gun4, CDS booster)**
- **INRNE Sofia: emittance measurement system (EMSY)**
- **INR Troitsk: CDS booster cavity**
- **LAL Orsay: high energy spectrometers**
- **LASA Milano: cathode system**
- **LNF Frascati: RF deflecting cavity**
- **MBI Berlin: laser system**
- **TU Darmstadt: beam dynamics simulations**
- **Uni Hamburg: bunch length measurement**
- **YERPHI Yerevan: accelerator controls**

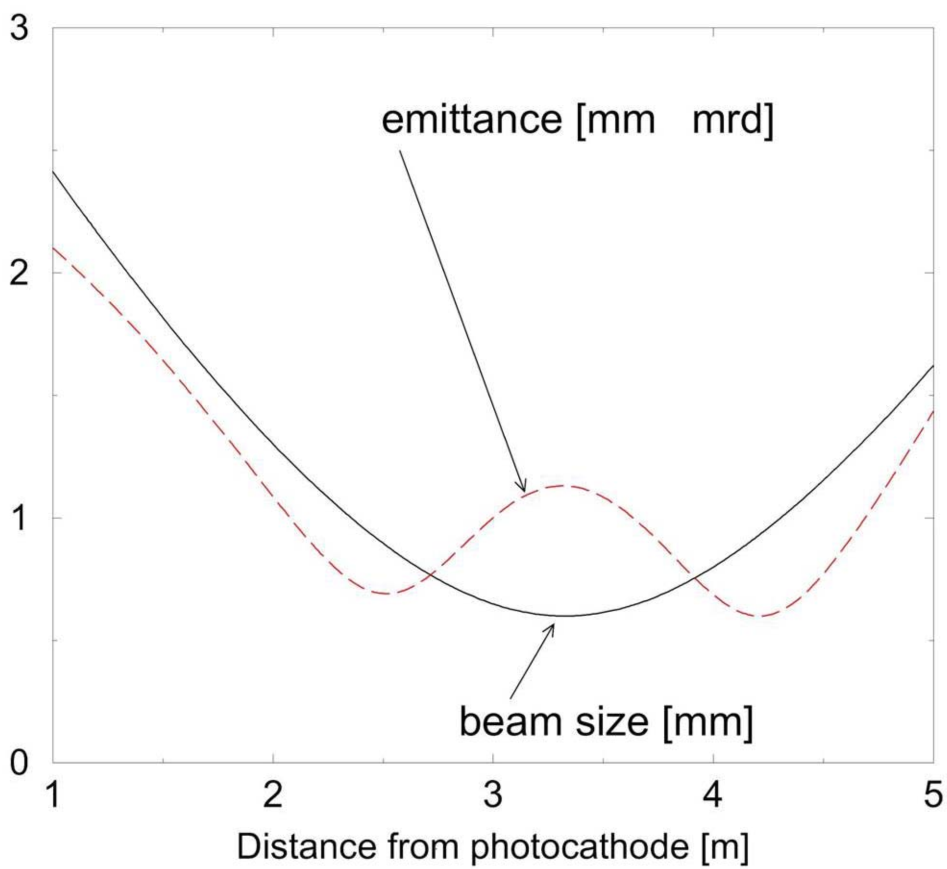



Funding through DESY (BMBF), HGF, EC (IA-SFS, EUROFEL)

Solenoid strength, drift length, and accelerating gradient are definded with the „invariant envelope“ technique:



→ place entrance of booster at local emittance maximum and beam size minimum

→ define accelerating gradient by:

$$\gamma'_{boost} = \frac{2}{\sigma_w}\sqrt{\frac{\hat{I}}{3I_0\gamma}}$$

γ'_{boost} = energy gain booster

σ_w = rms beam size

$\hat{I}$ = peak current

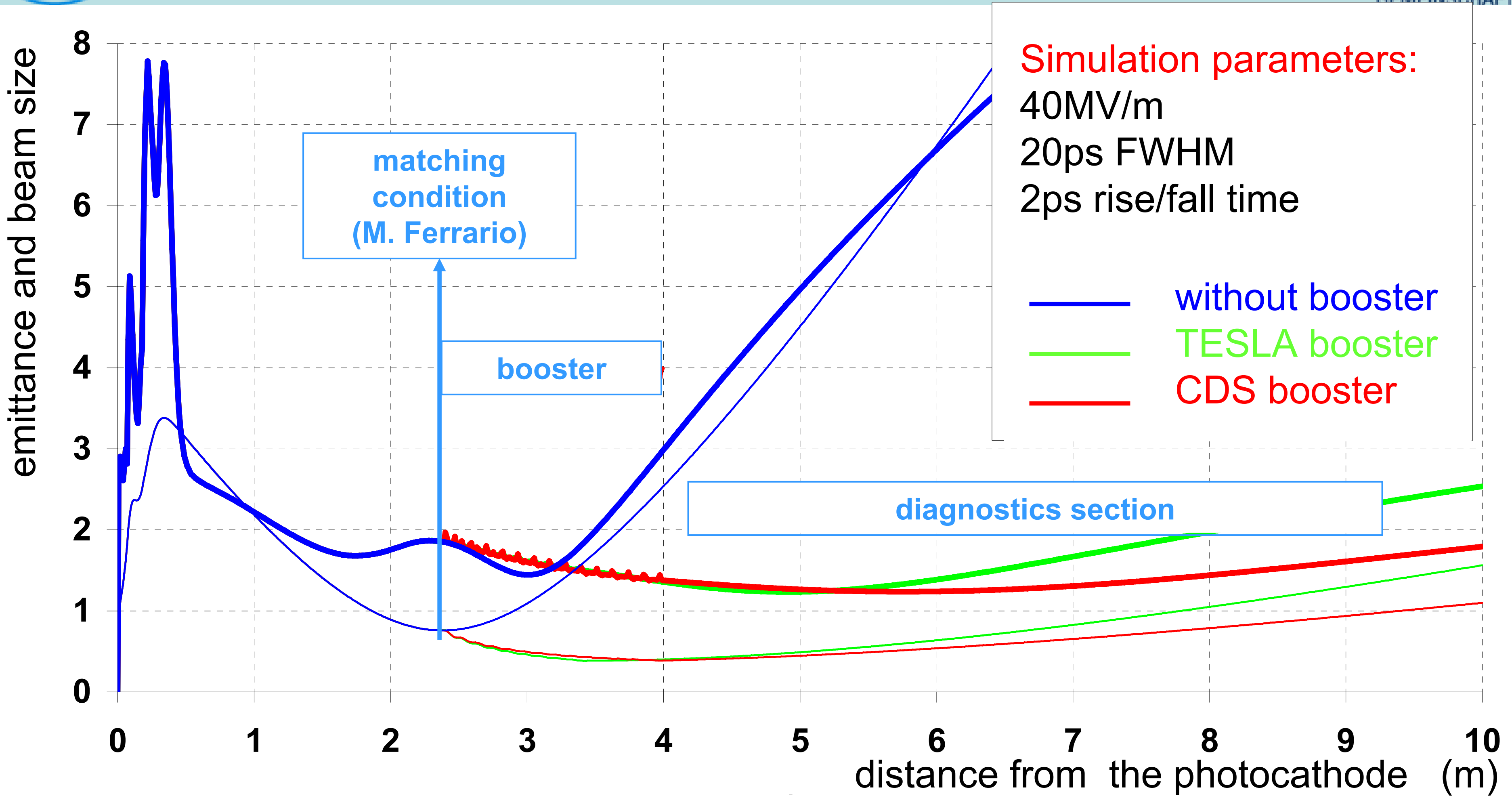
γ = mean beam energy

I_0 = Alvfen current

(17 kA for electrons)

The PITZ2 project

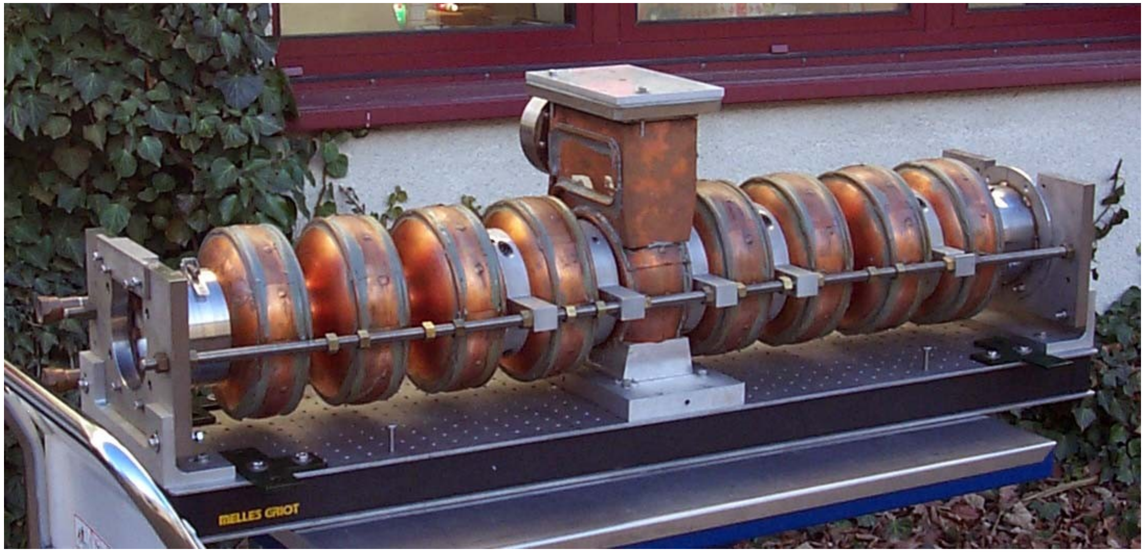
- Simulation of emittance conservation -

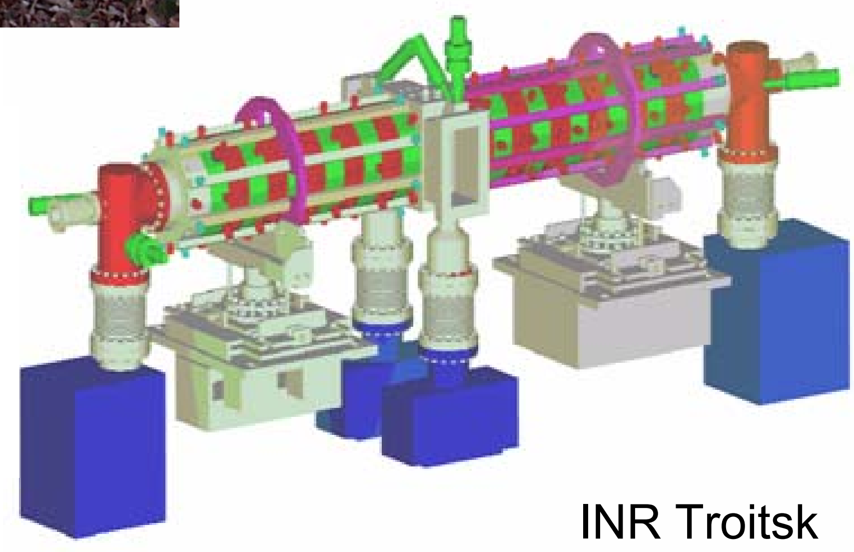


→ **check that the principle works and optimize it !**

Towards PITZ2

- The booster cavities -



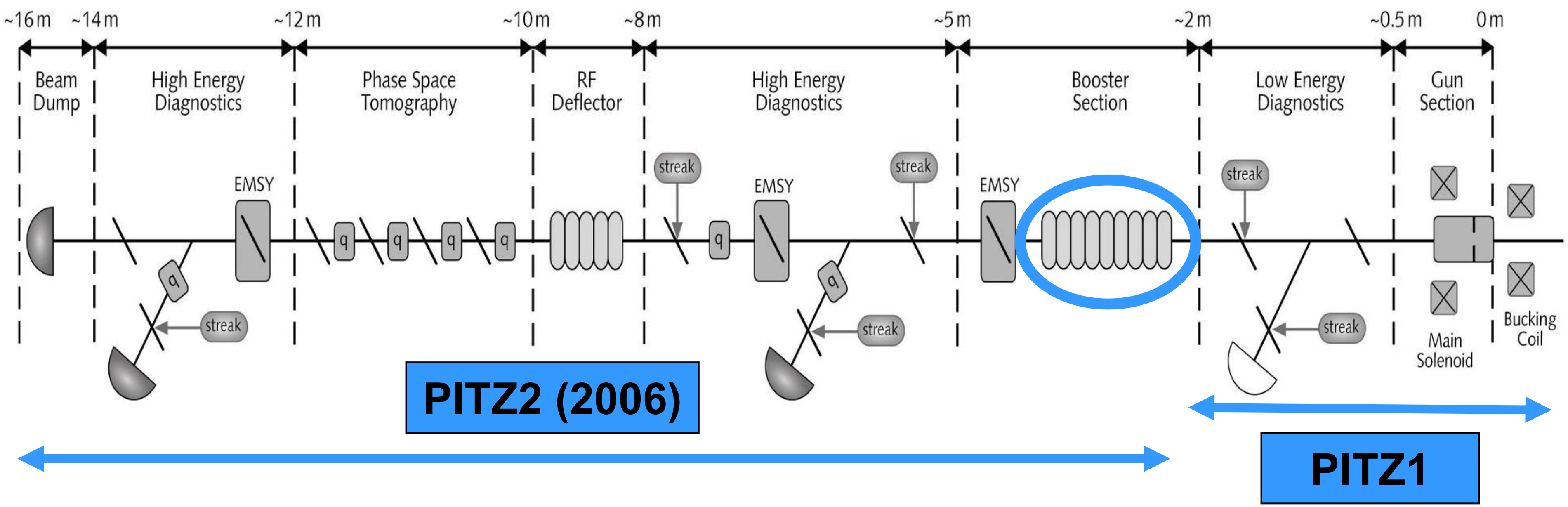


- use a n.c. TESLA prototype cavity as preliminary booster
- the final booster cavity specially designed for PITZ is in production and will be available in 2007

INR Troitsk

The PITZ2 project

- The facility upgrade -



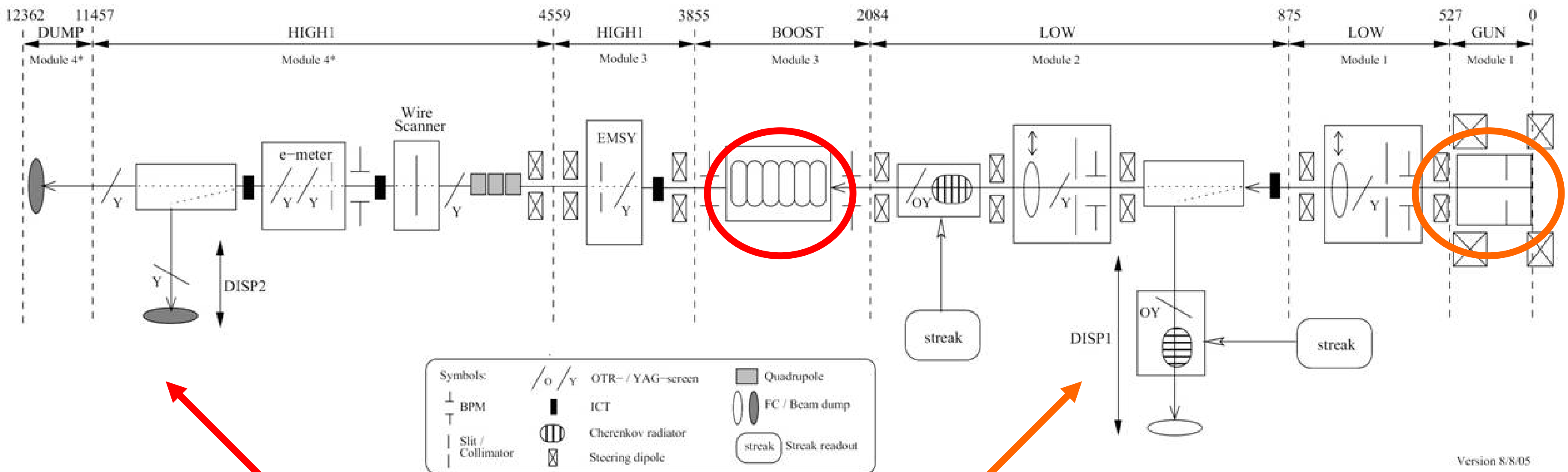
For the realization of PITZ2

- upgrade power and cooling systems
- take into operation a 2nd RF system for the booster
- install booster, beam dump, new diagnostics

→ start with a minimum version of PITZ2

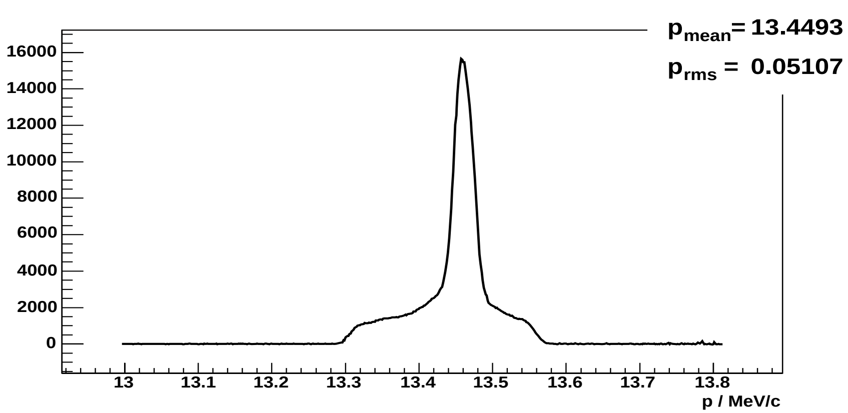
Towards PITZ2

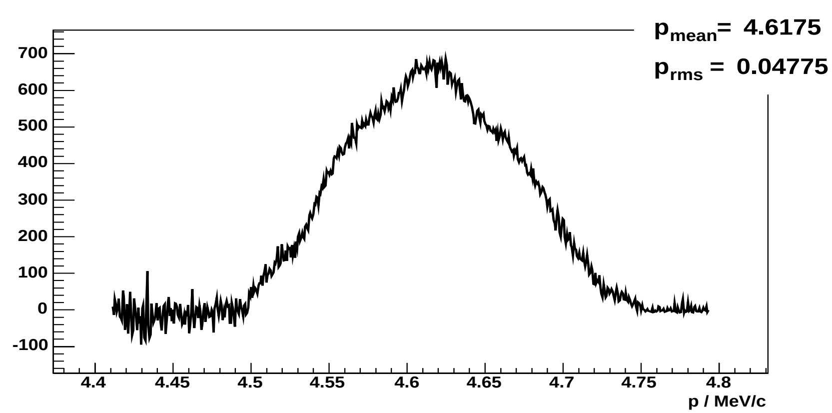
- The PITZ1.5 setup-



after the booster: 13.4 MeV

after the gun: 4.6 MeV





Towards PITZ2

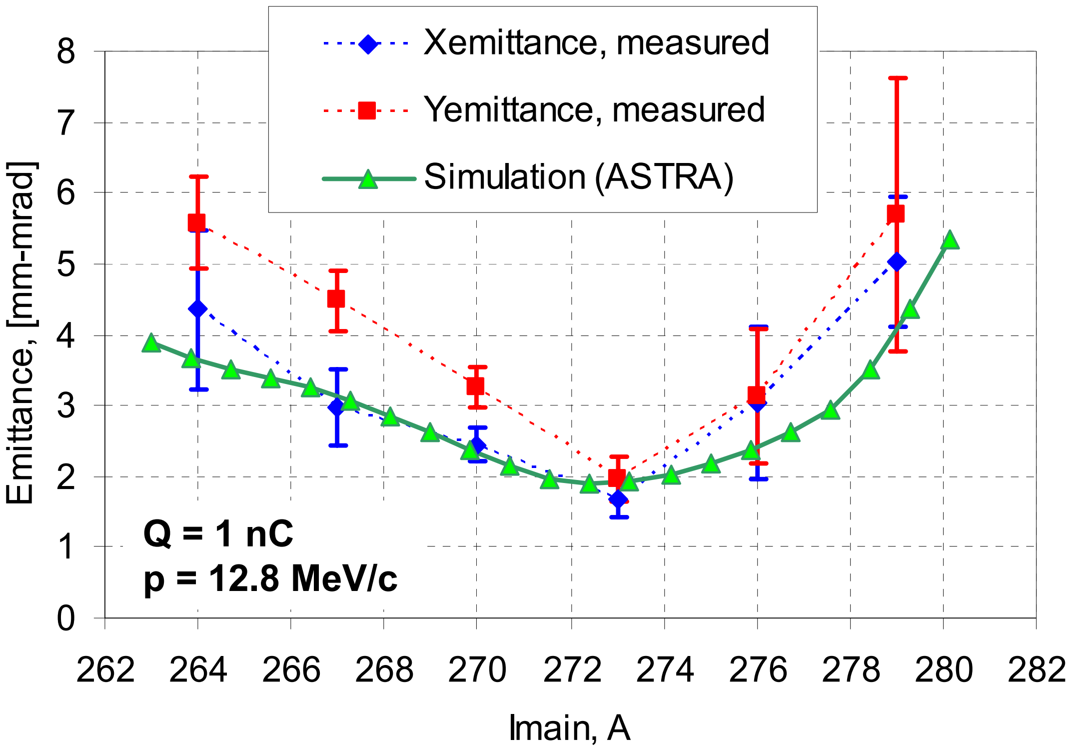
- The PITZ1.5 setup -

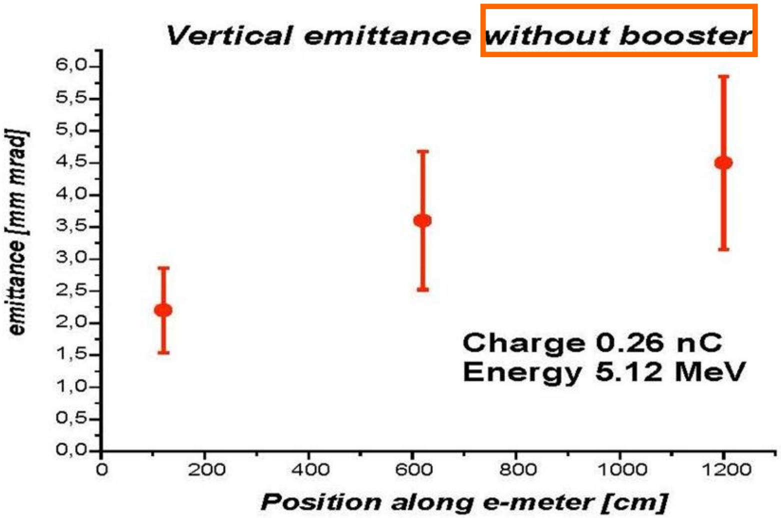
View of the extended PITZ facility (Summer 2005)

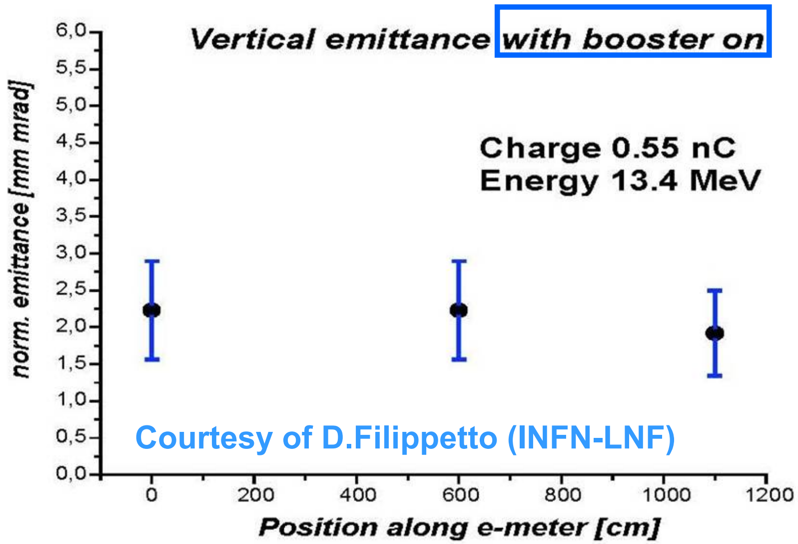
Towards PITZ2

- First results from PITZ1.5 -

- commissioning of new diagnostics
- studies of energy gain in gun and booster
- comparison of emittance measurements with EMSY (PITZ) and e-meter (LNF)





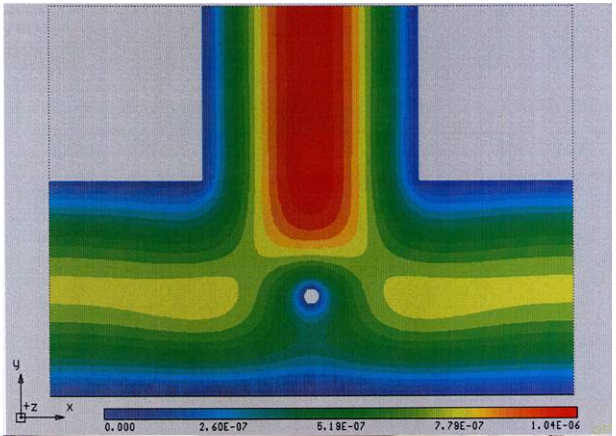


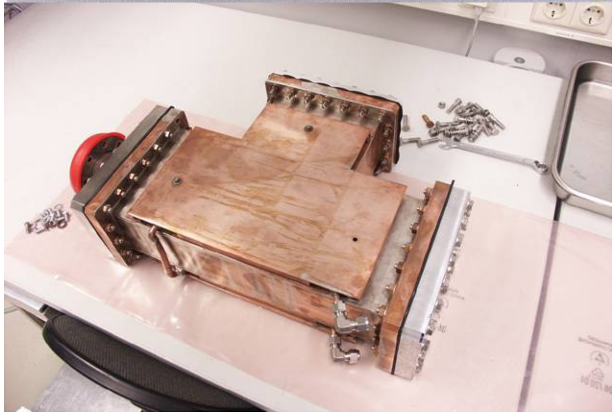
Courtesy of D.Filippetto (INFN-LNF)

Towards PITZ2

- The 10 MW MBK klystron -

- 10 MW klystron necessary to reach gradients above 42 MV/m in the gun
- use multi beam klystron from Thales
- RF output via two 5 MW arms → power combiner needed





Towards PITZ2

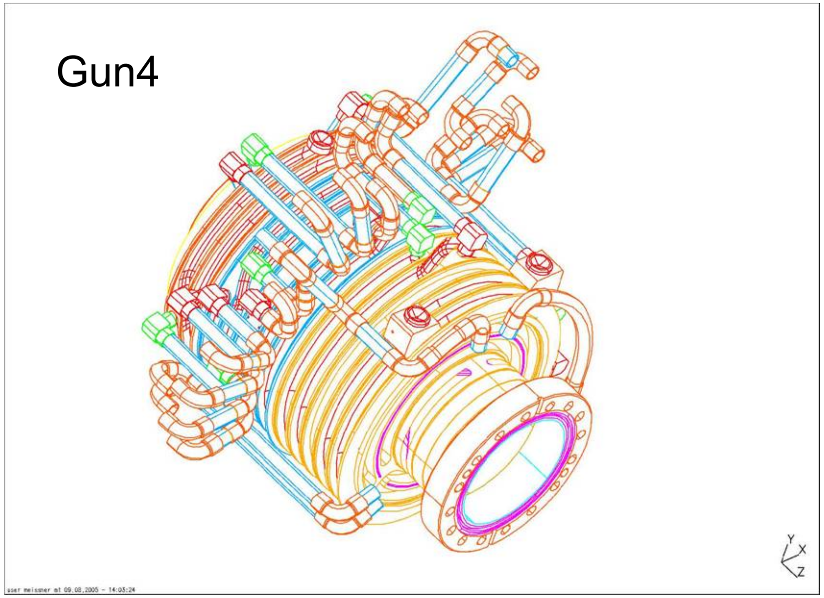
- High power tests of a gun cavity-

- Gun1 with 10 MW klystron tested up to ~57 MV/m in 2005
- Goal for XFEL: reach 60 MV/m → continue tests in 2006

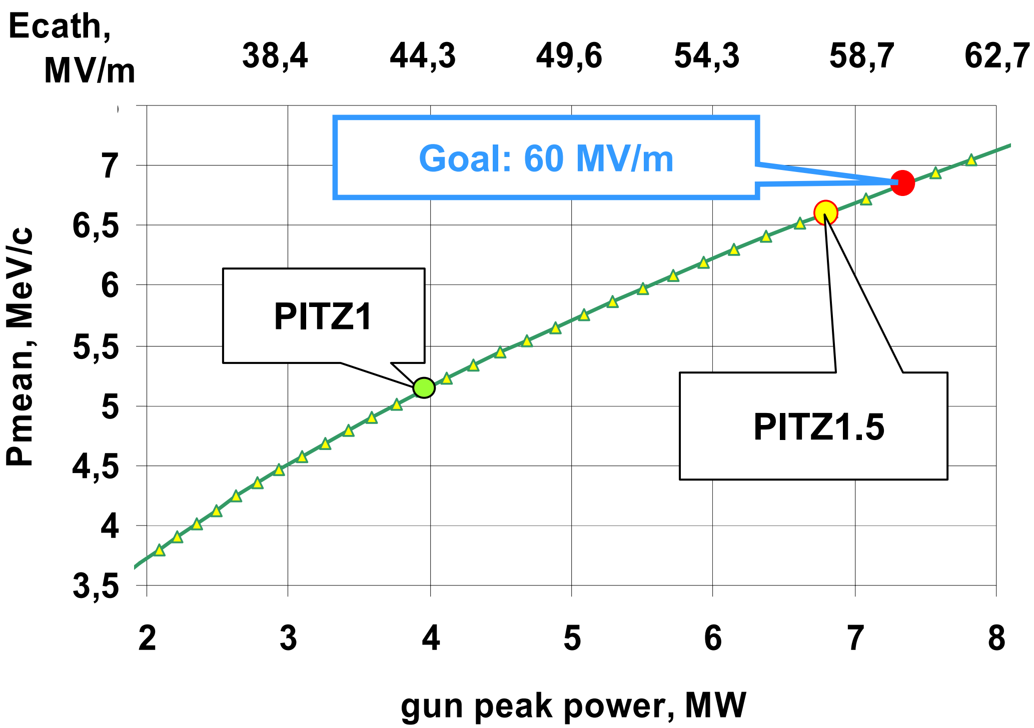
Problem:

thermal load of the gun →

new gun with improved cooling



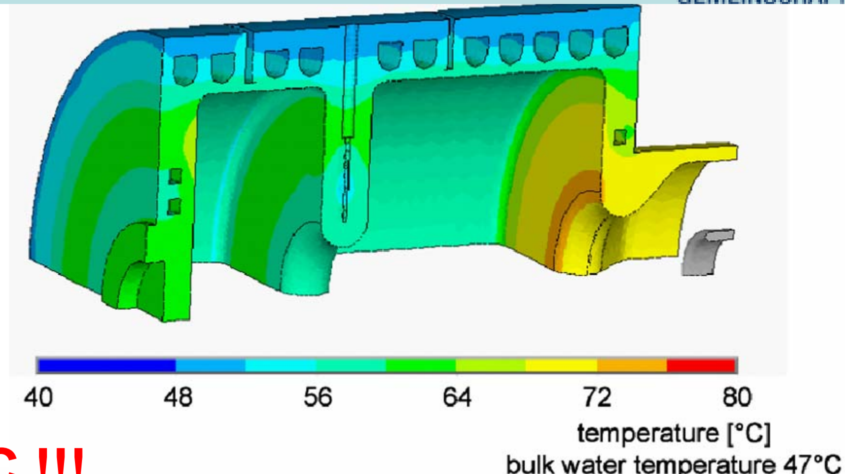
max. mean momentum ↔ gun power



Towards PITZ2

- High power tests of a gun cavity-

Calculations of thermal load:



- **27 kW of average RF power: ⇒ 80°C**

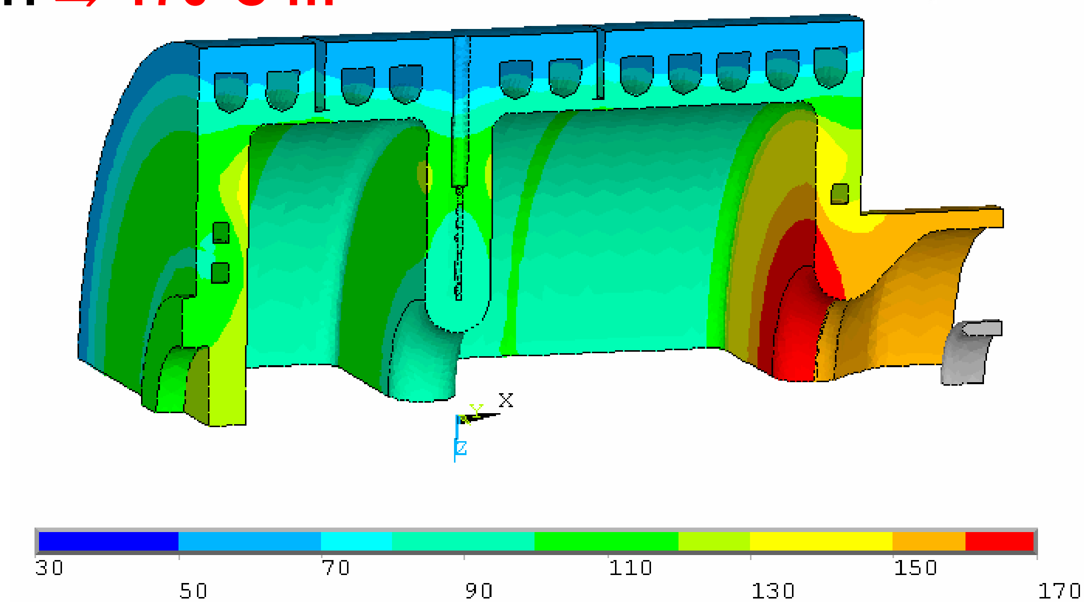
  (40MV/m, 900µs, 10 Hz) ✓**done (PITZ1)**

- **130 kW of average RF power: ⇒ 170°C !!!**

  (60MV/m, 650µs, 30 Hz)

➡

- **vacuum**
- **dark current**
- **new cathodes !!!**
- **new gun geometry ?**



Courtesy of Frank Marhauser (BESSY)

Summary

- sophisticated e^- sources are needed for the operation of FELs
  → RF photo cathode guns
- **PITZ** is a dedicated test facility at DESY in Zeuthen
- **PITZ1** has been successfully finished, and a completely characterized gun has been installed at the VUV-FEL
- the facility upgrade is ongoing, a preliminary booster and first **PITZ2** diagnostics have been taken into operation
- next steps are: study emittance conservation principle and approach the XFEL emittance requirements
- in parallel: do gun power tests and prepare new guns