Developing an Eletron source for the XFEL -

the Photo Injector Test Facility at Zeuthen, PITZ

- **Introduction, Motivation & Parameters**
- **Examples of International Experimental Results on Photo Injector Developments**
- **Results obtained in Zeuthen**
- **Further Developments needed to reach the XFEL Requirements**
- **Summary**

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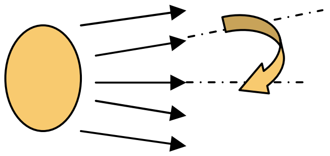
General Goal of the PITZ Facility

develop an electron source with minimum transverse emittance !

for the operation of the VUV-FEL and the XFEL

What is Emittance ?

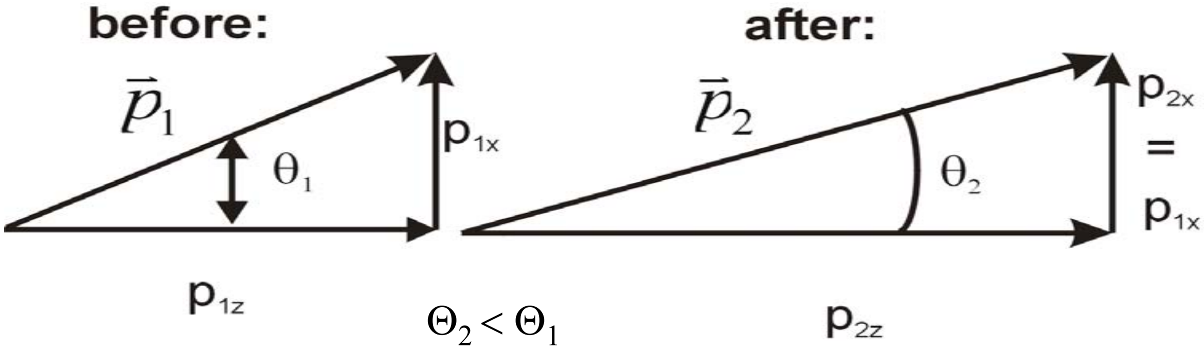


$\varepsilon_{x,y}$ ~ (e$^-$ beam size) • (e$^-$ beam angular divergence)

ε_z ~ (e$^-$ bunch length) • (energy spread of e$^-$ bunch)

ε = 6 dimensional phase space volume

acceleration (adiabatic damping):



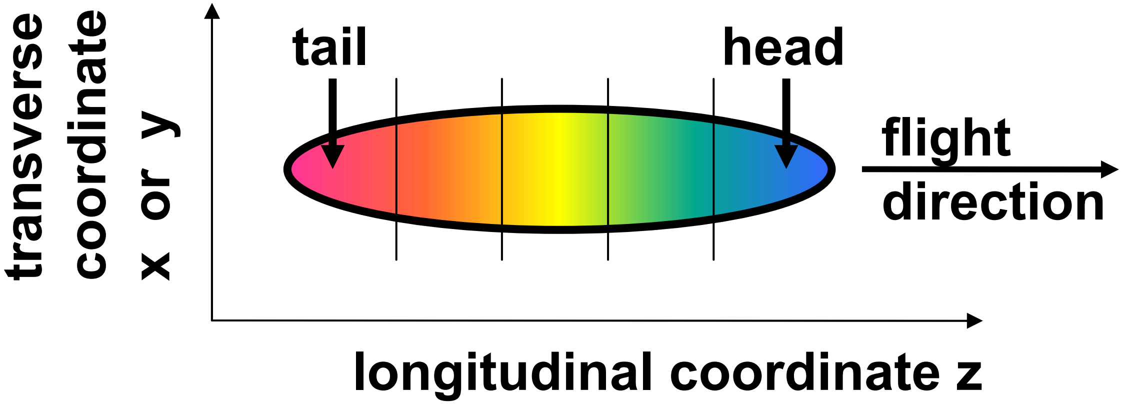
⇒ angular divergence is reduced

⇒ normalized transverse emittance:

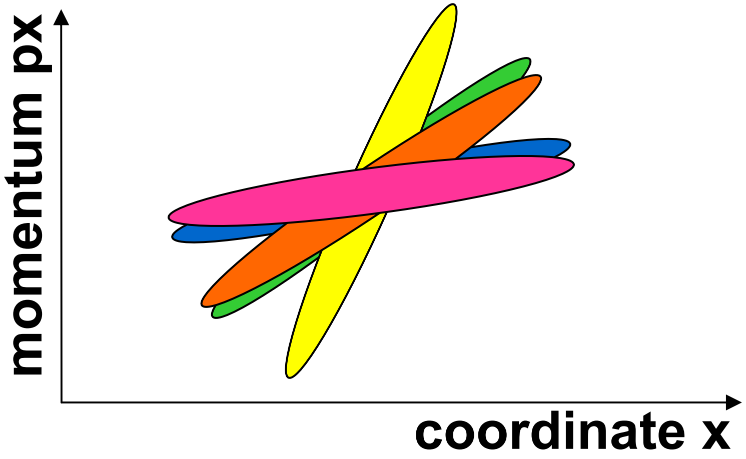
$$\varepsilon_x^n = \beta \bullet \gamma \bullet \sqrt{\sigma_x^2 \bullet \sigma_{x'}^2 - \mathrm{cov}^2(x, x')}\,; \quad \beta = \frac{v}{c}, \quad \gamma = \frac{1}{\sqrt{1 - \beta^2}}, \quad x' = \frac{dx}{ds}$$

(ε^n is conserved in general)

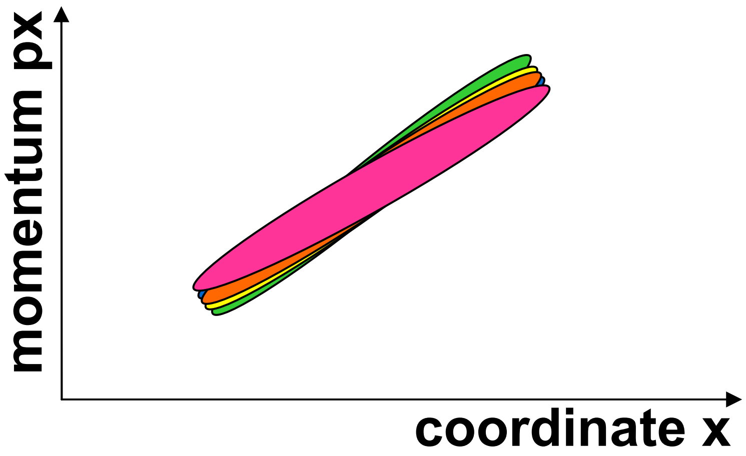
Slice Emittance vs. Projected Emittance



transverse phase space x↔px



transverse phase space x↔px

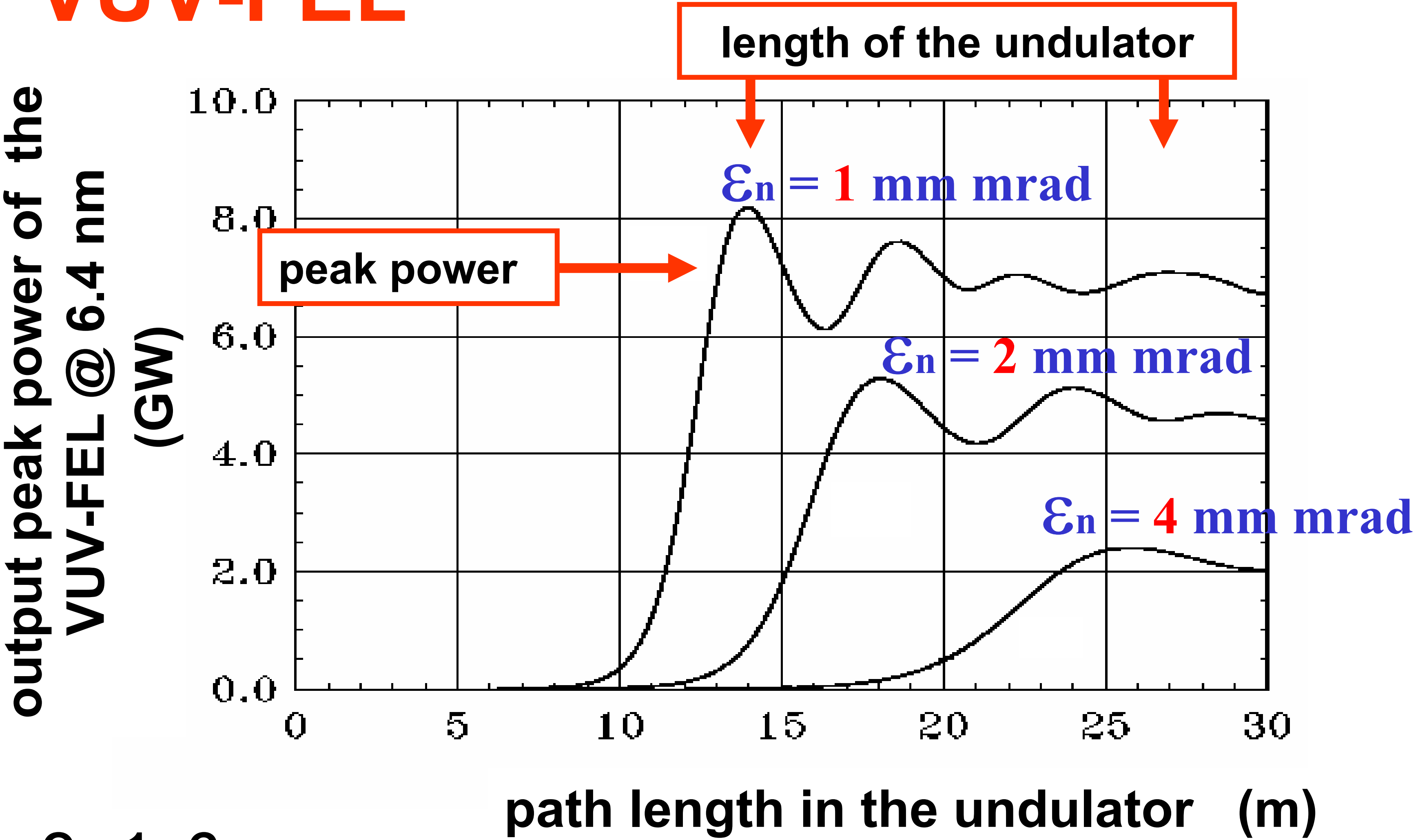


large ← projected emittance → small

- meas. projected emittance ≥ slice emittance ↔ FEL process

Motivation: Why small emittance is important

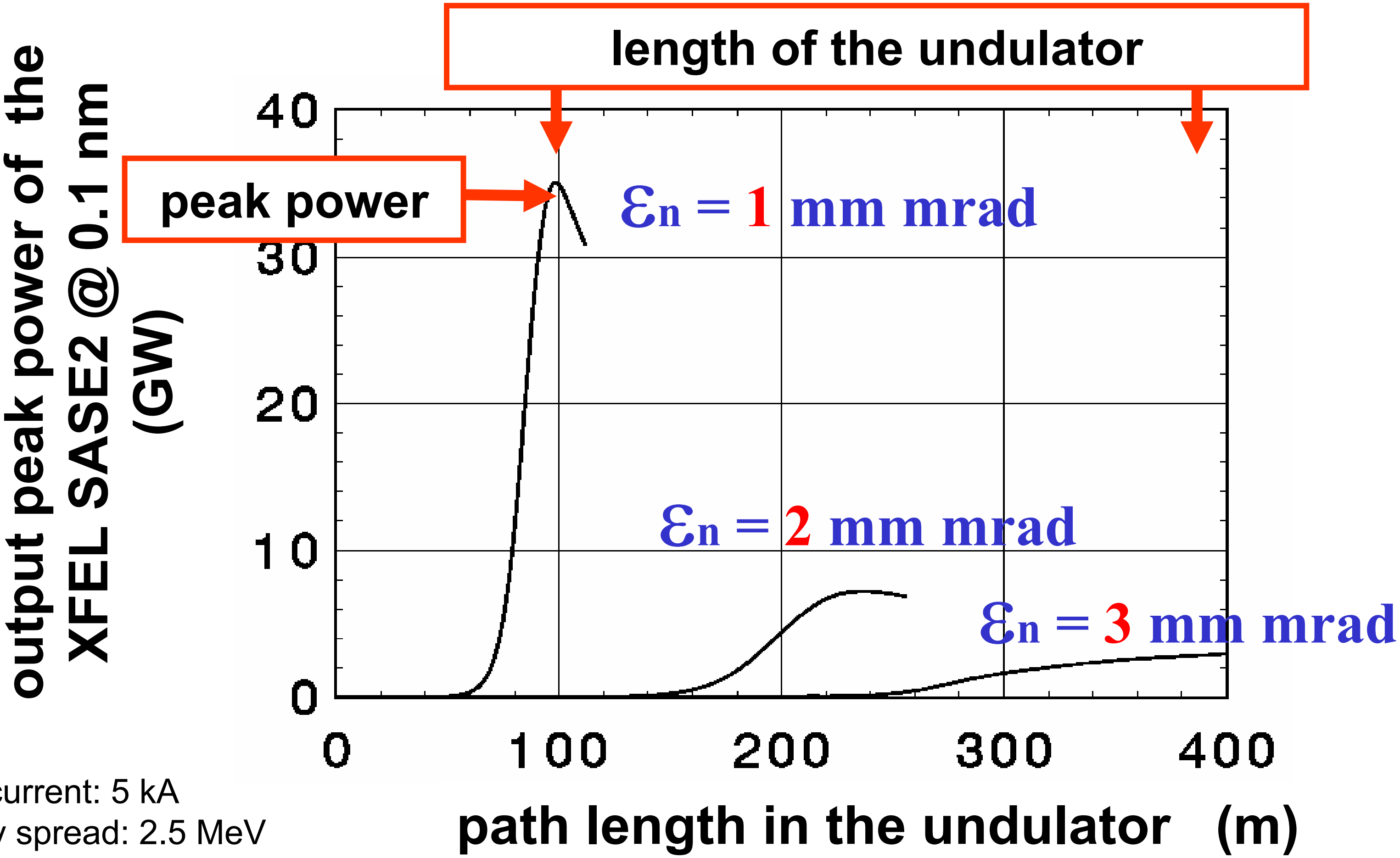
VUV-FEL



Q = 1 nC

Motivation: Why small emittance is important

XFEL

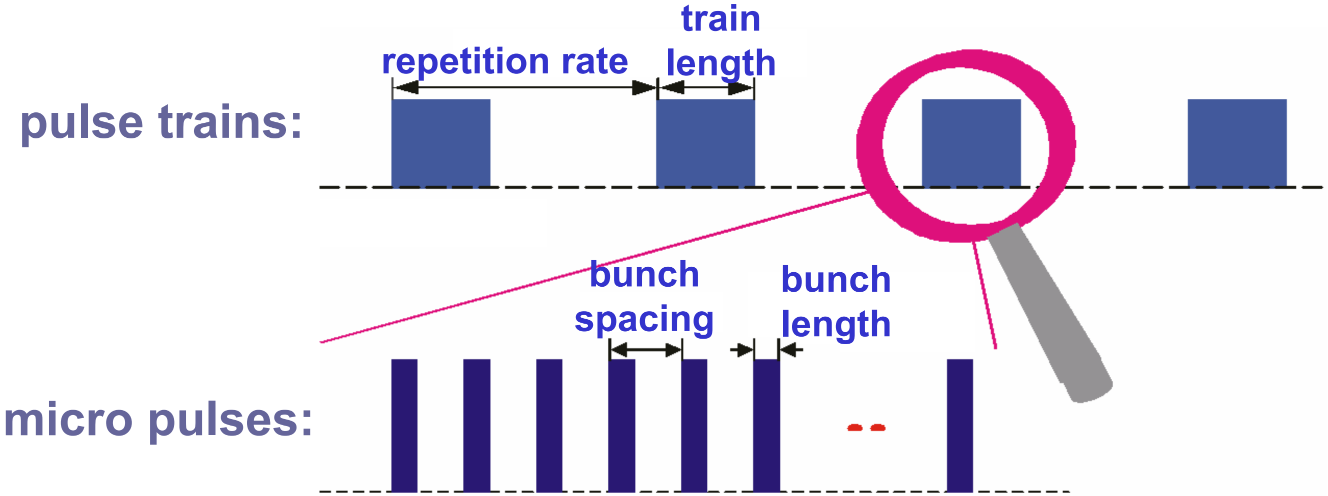


peak current: 5 kA
energy spread: 2.5 MeV

- **XFEL goal: 0.9 mm mrad@injector = 1.2 mm mrad@undulator**
- **smaller emittance ⇒ new horizons:**

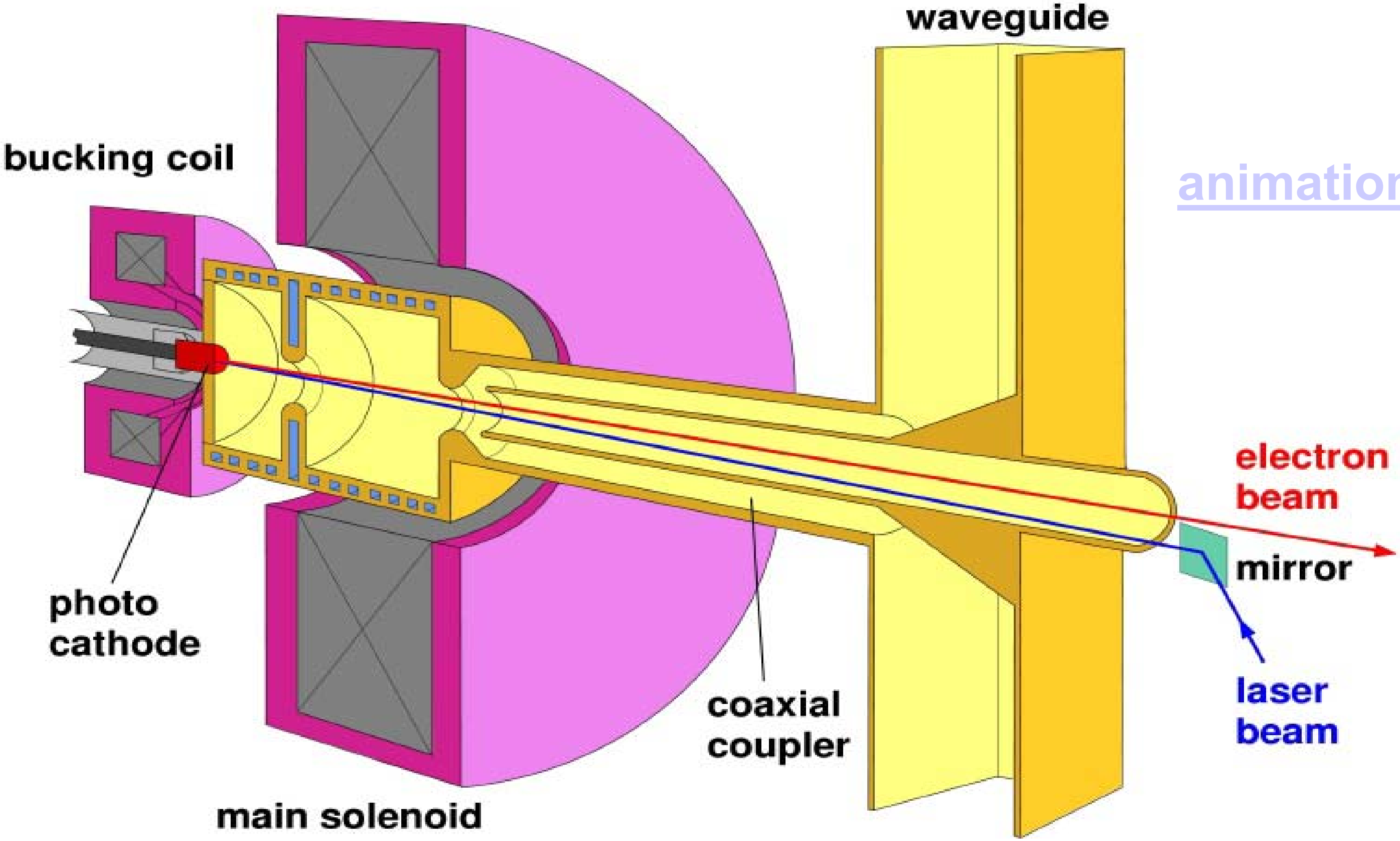
shorter wavelength, less energy required

Some Parameters of the VUV-FEL and the XFEL



Parameters	**VUV-FEL@TTF2**	**European XFEL**
final energy	1 GeV	20 GeV
bunch charge	1 nC	1 nC
max. repetition rate	10 Hz	10 Hz
max. train length	800 µs	650 µs
bunch spacing	0.11 – 1 µs	0.2 – 1 µs
required injector emittance	2 mm mrad	0.9 mm mrad
SASE output wavelength	6.4 – 30 nm	0.1 – 6.4 nm

Schematic of the RF Gun used at PITZ



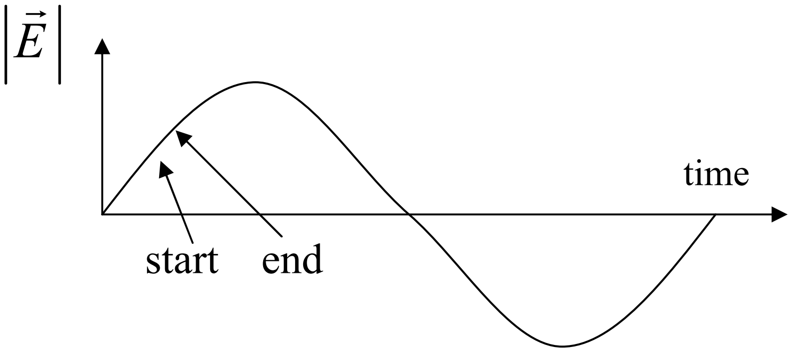
animation

RF Guns

FELs need high space charge density (small $\varepsilon_{x,y}$, small ε_z , medium Q)

related problems are e.g.:

- launch of e⁻ at optimal rf phase:



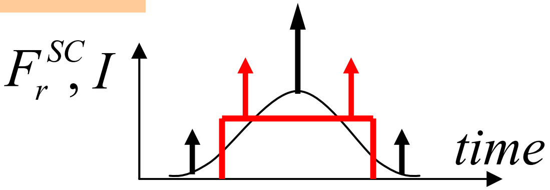
- defocussing space charge force:

$$F_r^{SC} \propto Q \frac{r}{\gamma^2}$$

- focussing solenoid strength:

$$F_r^{sol} \propto -r$$

- laser parameters (trans., long.): homogenous



Projected Emittance Measurements at ATF@BNL

parameters:

* 0.5 nC

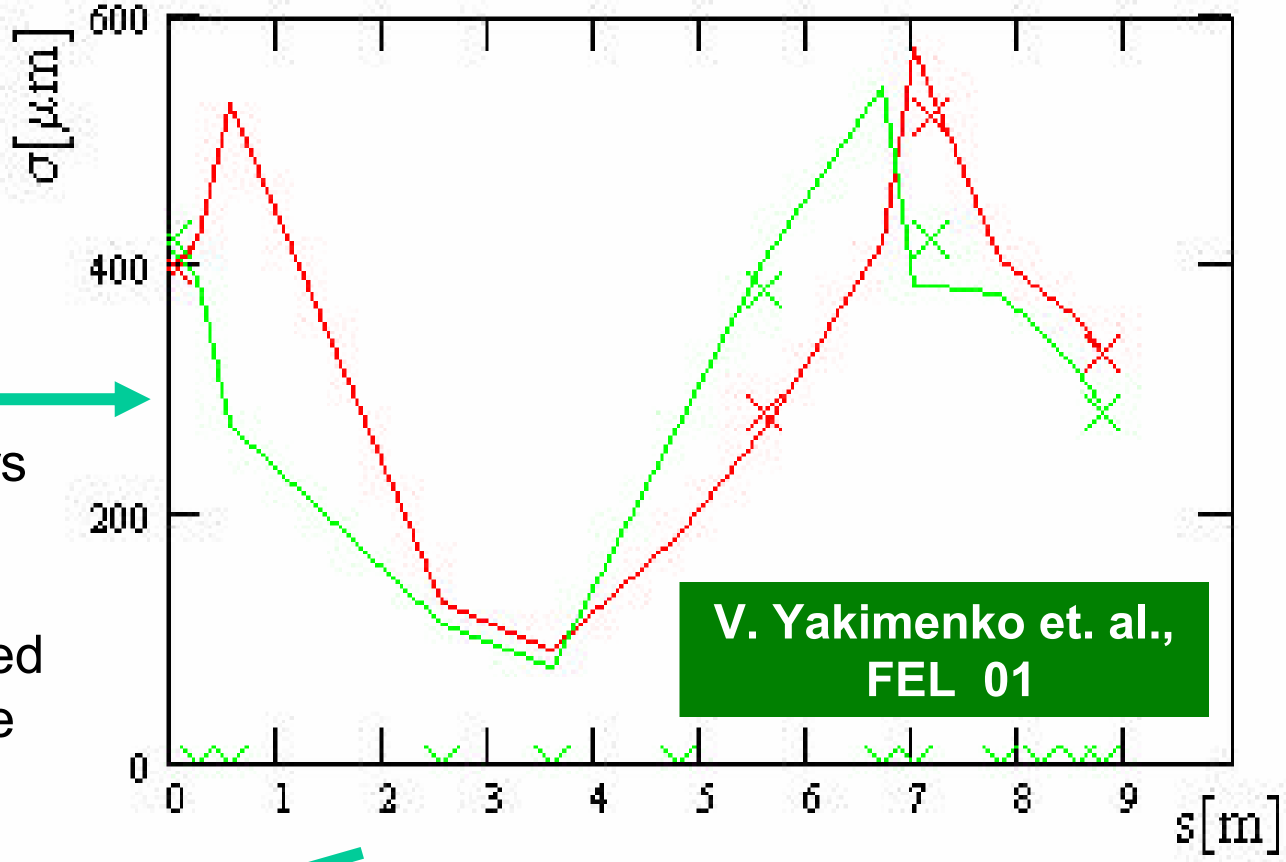
* 110 MV/m at gun

* beam energy: 60 MeV

methode:

* fitting Twiss parameters to 4 subsequent beam size measurements

* transport optics adjusted to maximize beam size at screen locations



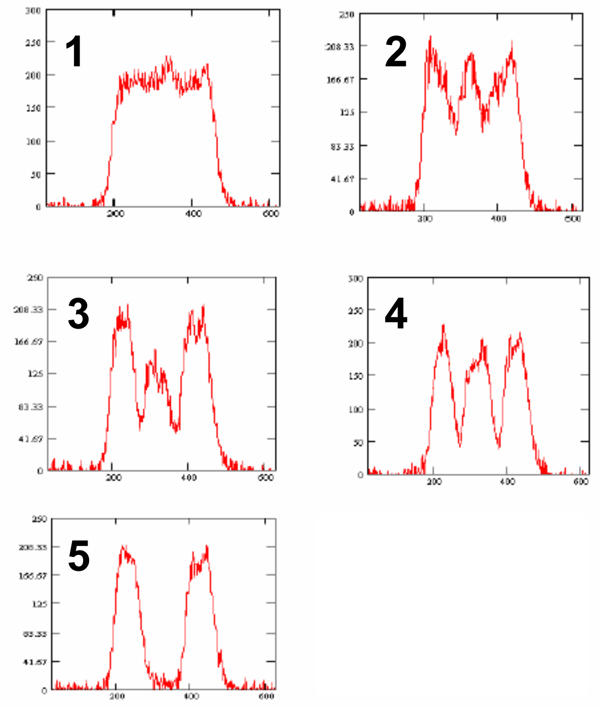
V. Yakimenko et. al., FEL 01

fit result:

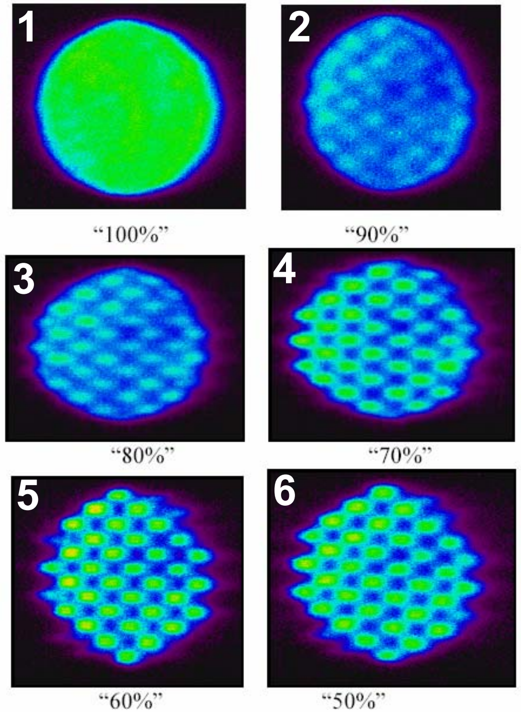
ε_n = 0.8 mm mrad for 0.5 nC, accuracy: better than 15%

Transverse Laser Shape Studies from ATF@BNL

cylindical symmetric



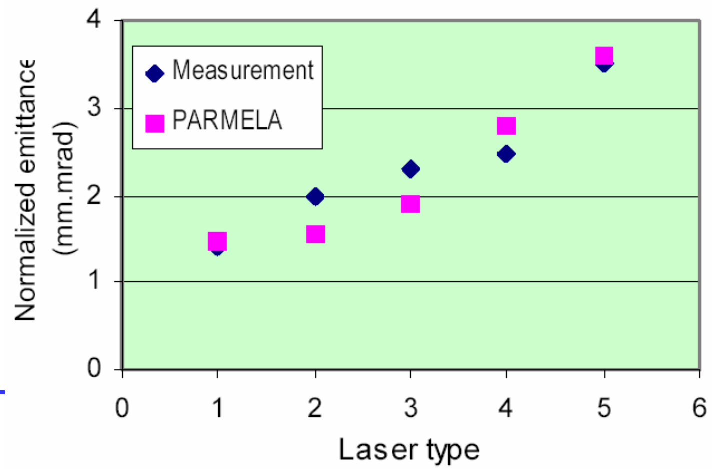
non-cylindical symmetric



"100%" "90%" "80%" "70%" "60%" "50%"

parameters:

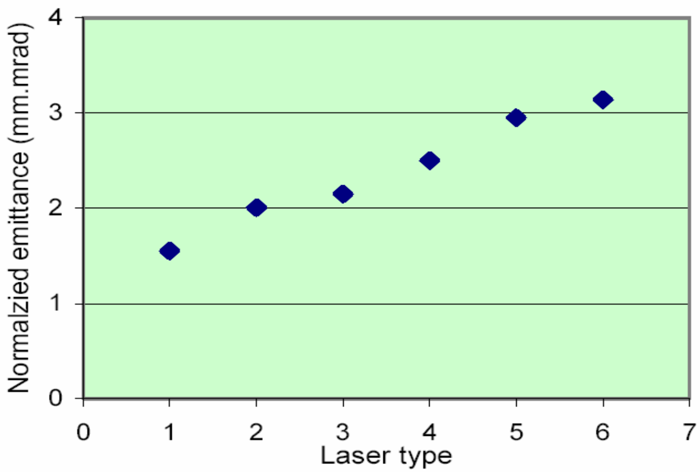
- 0.46 – 0. 48 nC
- phase: 30º from zero crossing
- emittance measured at 40 MeV via quad scan



additional study:

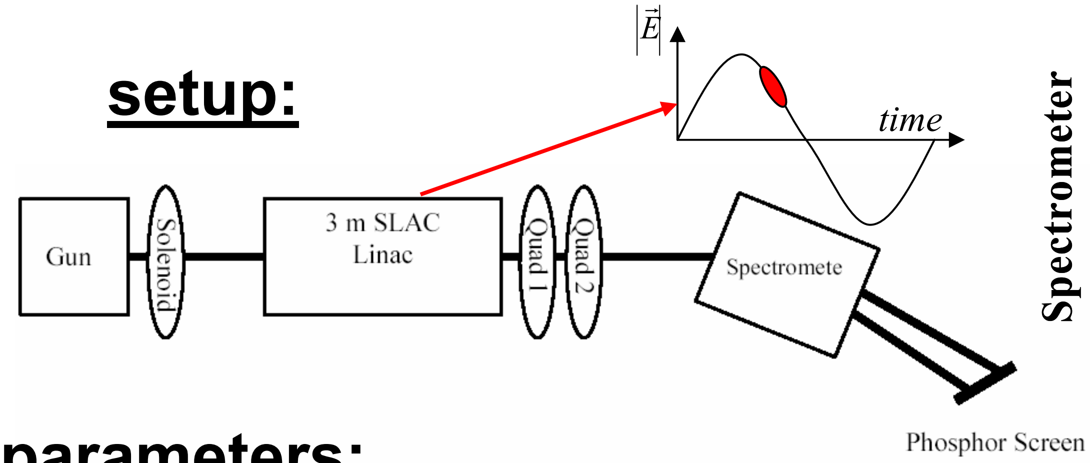
emittance vs charge ~ linear

F. Zhou et. al., EPAC 02

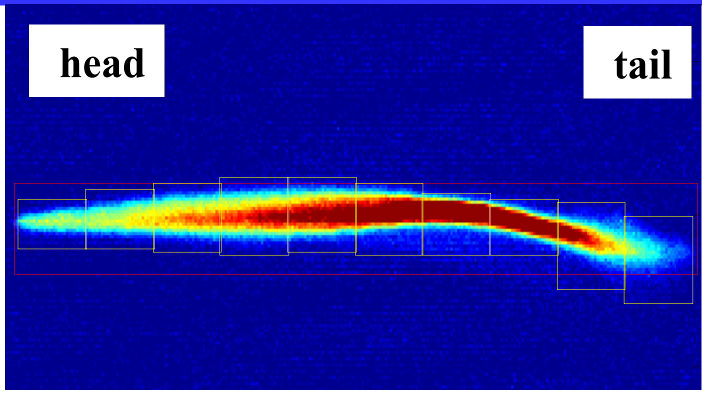


Slice Emittance Measurements from GTF@SLAC

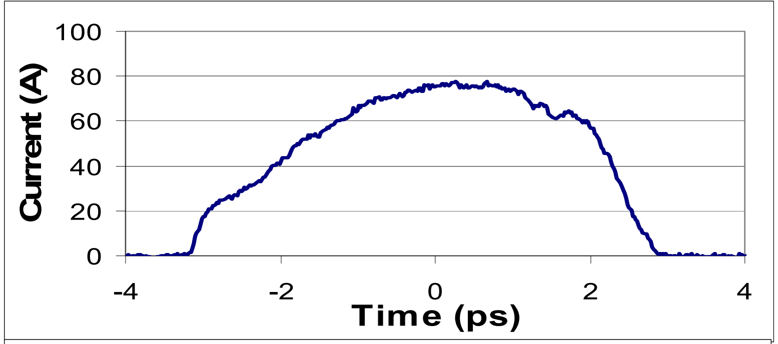
setup:

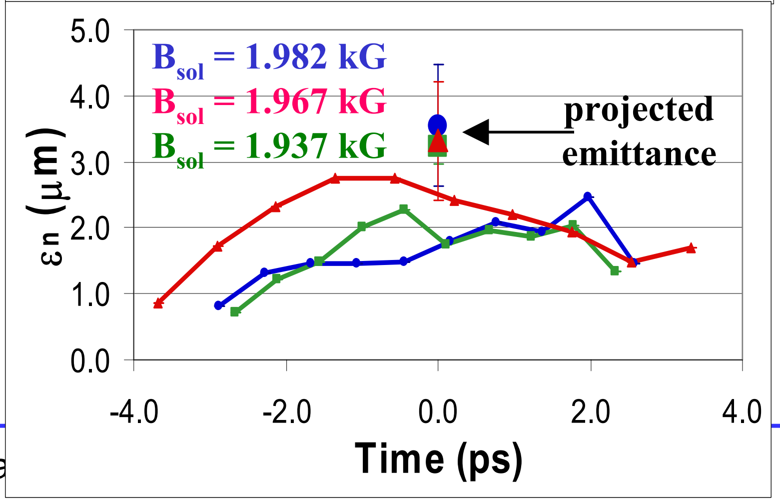


Spectrometer Image



Energy/Time





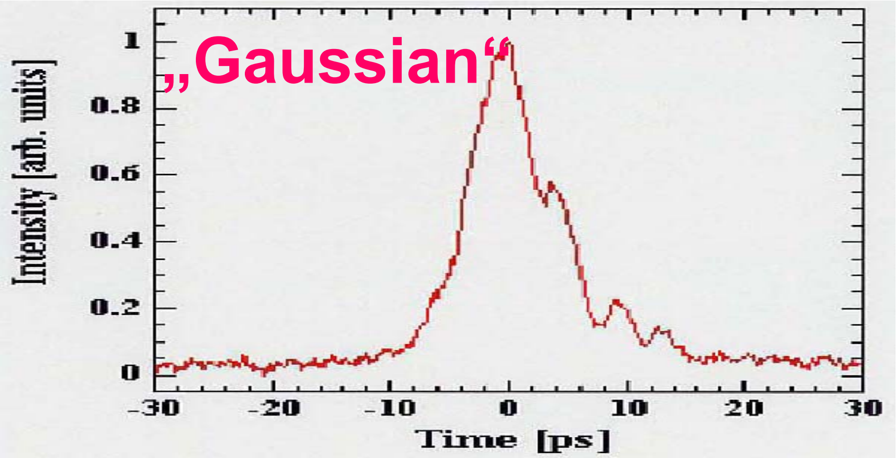
parameters:

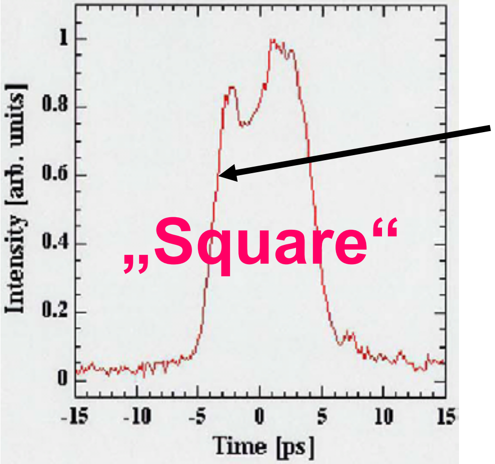
- 300 pC
- laser: 1.8 ps FWHM
  2 mm diameter on cathode
- phase: 30° from zero crossing
- slice width 550-750 fs
- beam size: signal cut at 5% of max.

D.H. Dowell et. al., LCLS-TN-03-2 (corr.)

WR on Emittance from SHI+FESTA@Japan

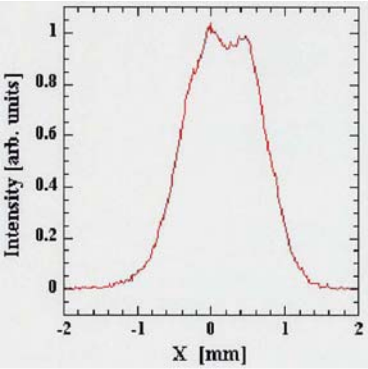
- **1.6 cell S-band gun (→ 4 MeV) + 70 cm SW linac (→ 14 MeV)**
- **Ti:Saphire laser system (→ 50 fs long pulses at 800 nm) + pulse shaping (e.g. gratings + liquid crystal spatial light modulator)**
- **temporal shape of laser pulses: (x-ray streak camera, resolution: ~2 ps)**

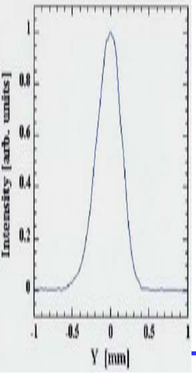




rise/decay time: 1.5 ps, limited by streak camera

- **transverse laser distributions: (cathode)**



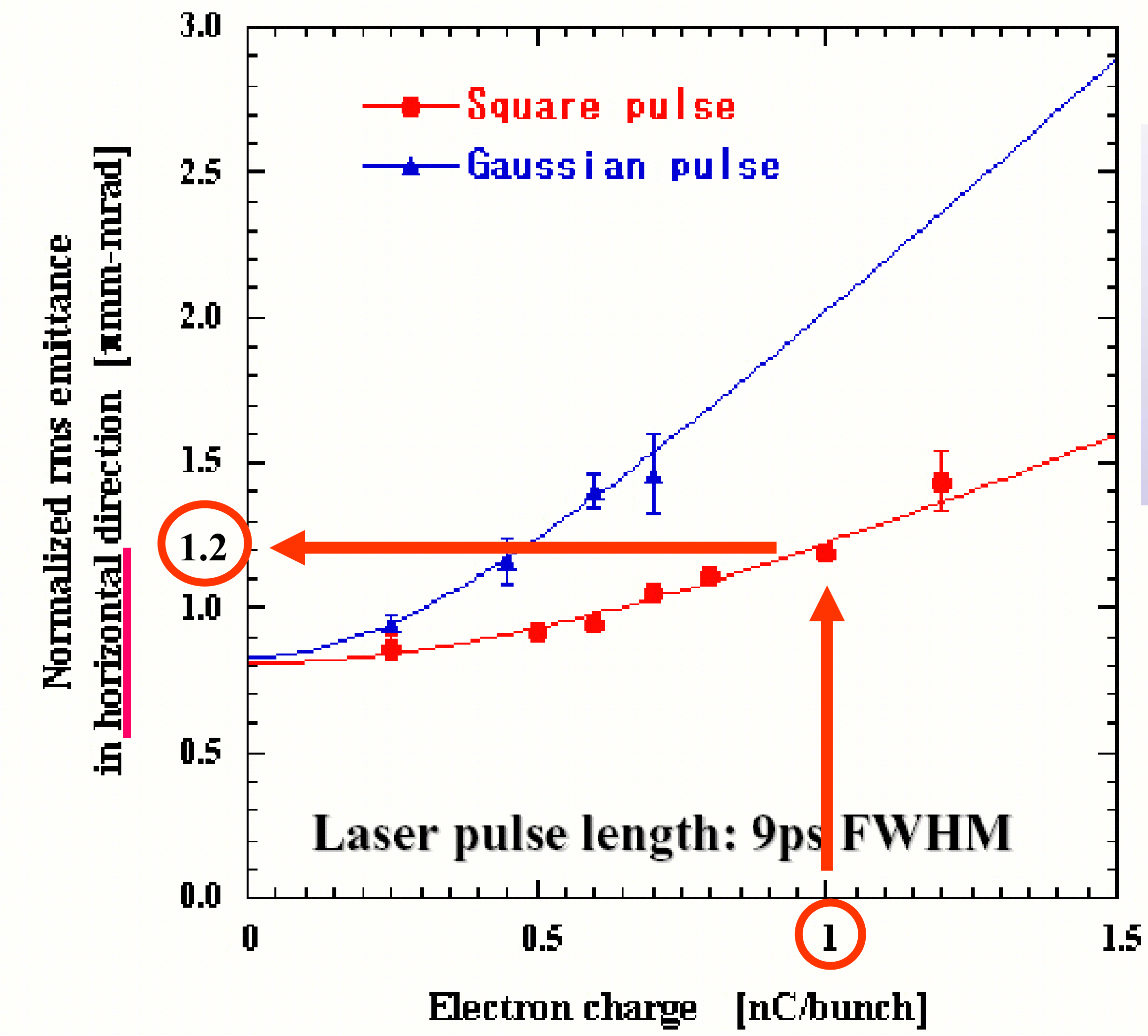


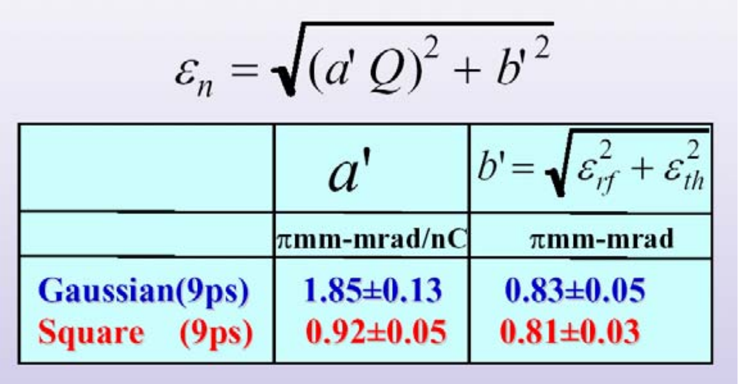
F. Sakai et. al., ICFA workshop 2002, SPring8

World Record on Emittance

Emittance measurements for gaussian and square laser pulse shapes

Methode: quad scan @ 14 MeV, gaussian fit to background subtracted signal frames





$$\varepsilon_n = \sqrt{(a' Q)^2 + b'^2}$$

	a'	$b' = \sqrt{\varepsilon_{rf}^2 + \varepsilon_{th}^2}$
	πmm-mrad/nC	πmm-mrad
Gaussian(9ps) Square (9ps)	1.85±0.13 0.92±0.05	0.83±0.05 0.81±0.03

For 1 nC:

$\varepsilon_n \approx 1.2$ mm mrad

F. Sakai et. al.,
ICFA workshop 2002, SPring8

Photo Injector Test Facility at Zeuthen (PITZ)

- Test facility for photo injectors: focus on VUV-FEL, XFEL

  ⇒ **very small transverse emittance (0.9 mm mrad @ 1 nC)**

  ⇒ stable production of short bunches with small energy spread

- Extensive R&D on photo injectors in parallel to TTF operation

- Compare detailed experimental results with simulations:

  ⇒ benchmark theoretical understanding of photo injectors

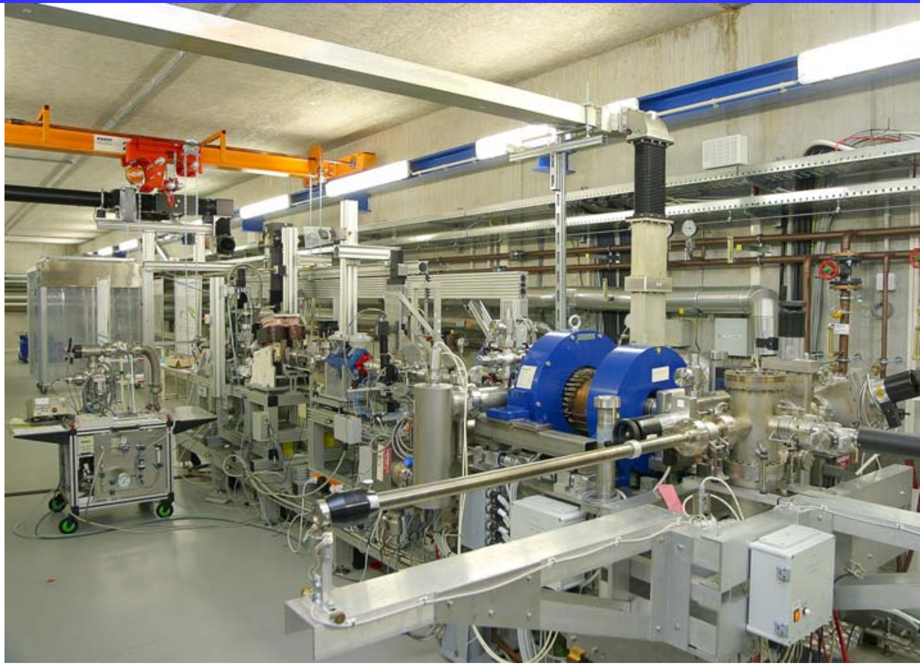
- Test and optimize RF guns for subsequent operation at VUV-FEL and XFEL

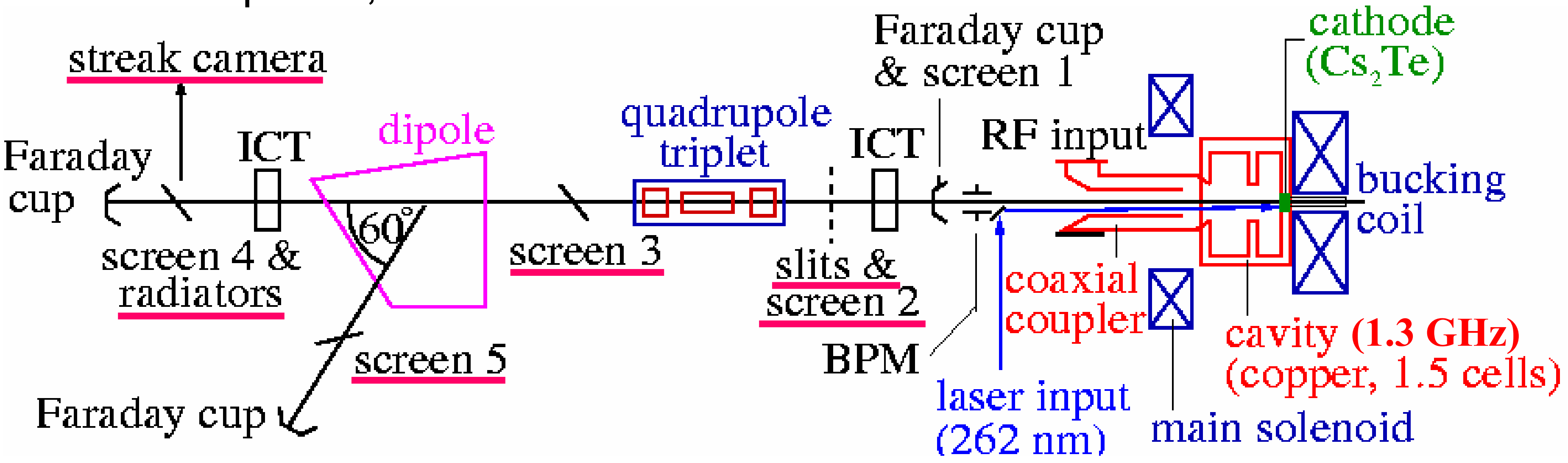
- Test new developments (laser, cathodes, beam diagnostics)

Short History and PITZ 1 Layout

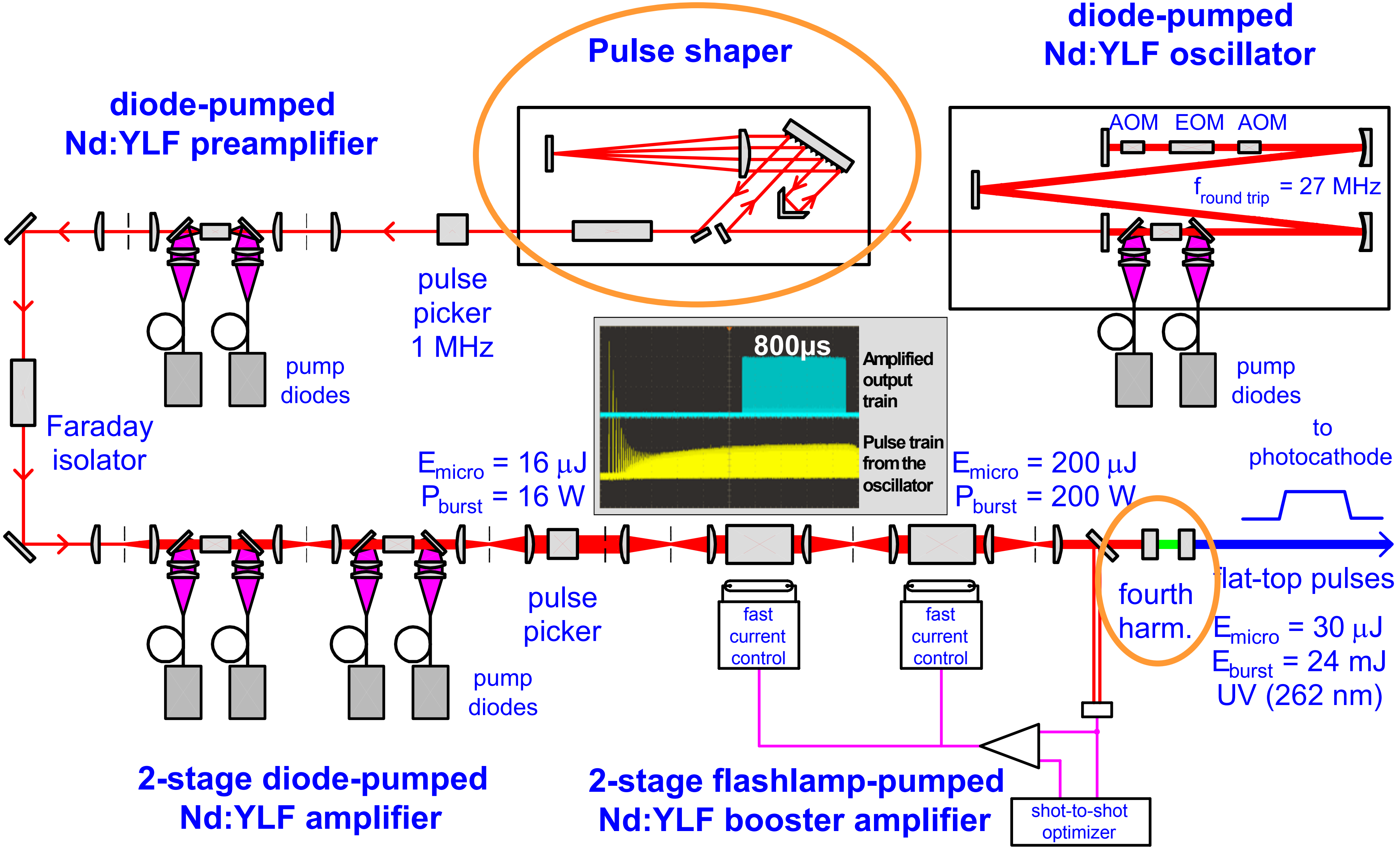
Short History of PITZ:

- autumn 1999: decission to built PITZ
- 2000: civil construction of buildings
- 2001: installation of infrastructure
- January 2002: first photo electrons
- 2002/2003: upgrade facility
- December 2003: characterization of gun prototype 2 finished → VUV-FEL
- 2004: install gun prototype 1, increase rf power, do characterization





Laser system from the MBI in Berlin



Pulse shaper

diode-pumped Nd:YLF oscillator

AOM EOM AOM

$f_{\text{round trip}}$ = 27 MHz

diode-pumped Nd:YLF preamplifier

pulse picker 1 MHz

pump diodes

pump diodes

Faraday isolator

800µs

Amplified output train

Pulse train from the oscillator

$E_{\text{micro}} = 16\ \mu J$
$P_{\text{burst}} = 16\ W$

$E_{\text{micro}} = 200\ \mu J$
$P_{\text{burst}} = 200\ W$

to photocathode

pulse picker

fast current control

fast current control

fourth harm.

flat-top pulses

$E_{\text{micro}} = 30\ \mu J$
$E_{\text{burst}} = 24\ mJ$
UV (262 nm)

pump diodes

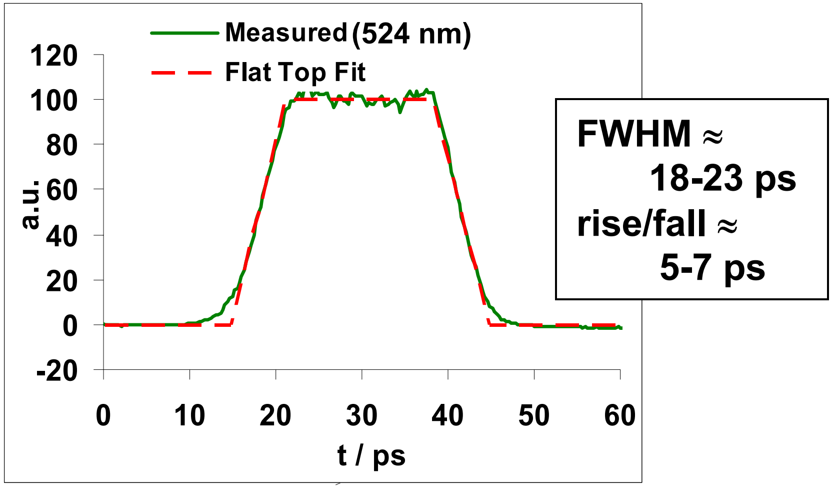
shot-to-shot optimizer

2-stage diode-pumped Nd:YLF amplifier

2-stage flashlamp-pumped Nd:YLF booster amplifier

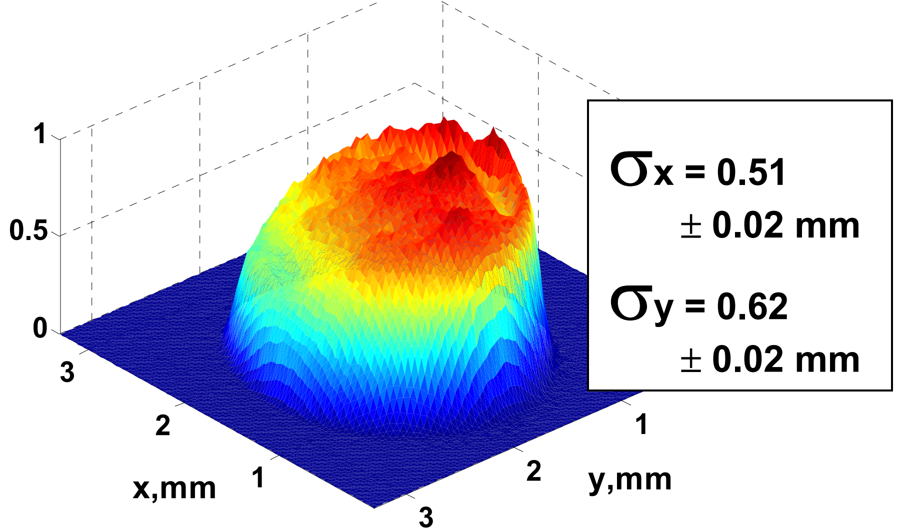
Temporal and Transverse Laser Profiles

in 2003 (VUV-FEL gun):



FWHM ≈ 18-23 ps

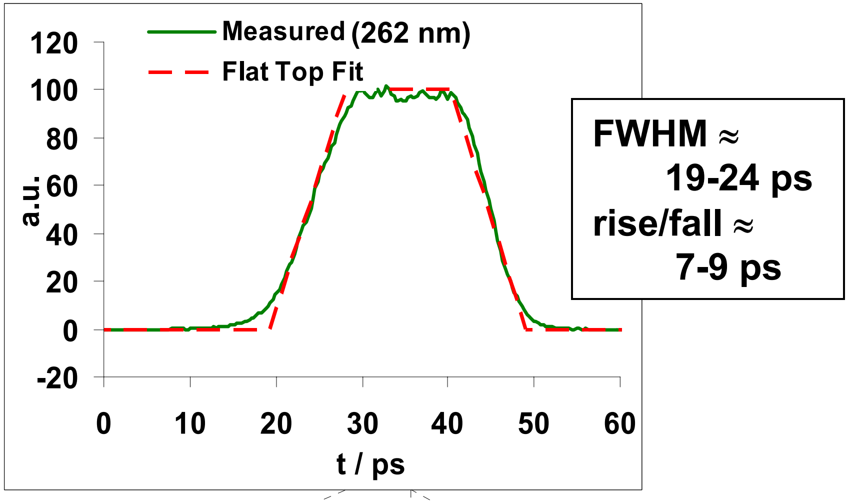
rise/fall ≈ 5-7 ps



σx = 0.51 ± 0.02 mm

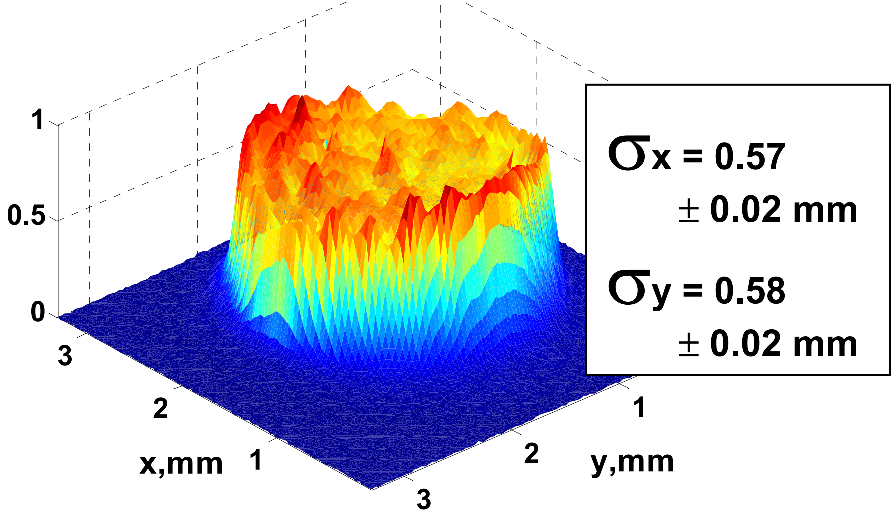
σy = 0.62 ± 0.02 mm

in 2004 (gun prototype #1):



FWHM ≈ 19-24 ps

rise/fall ≈ 7-9 ps



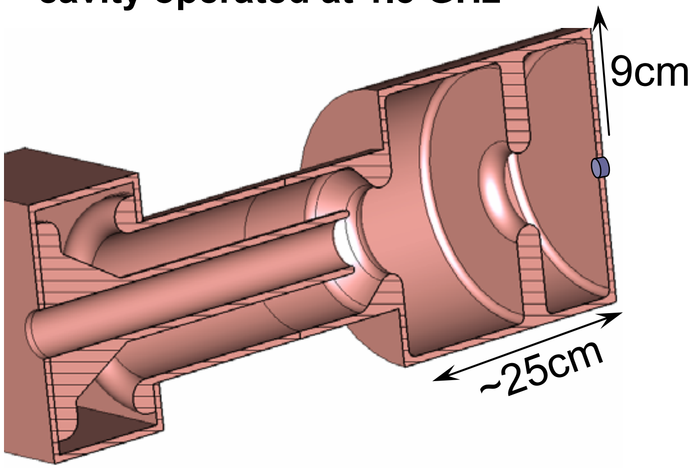
σx = 0.57 ± 0.02 mm

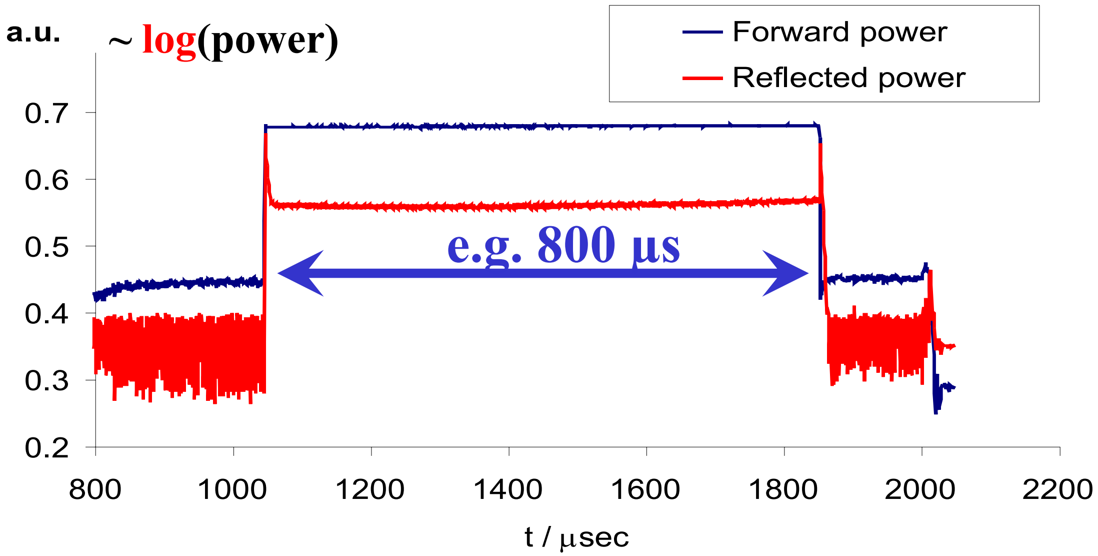
σy = 0.58 ± 0.02 mm

VUV-FEL Gun: long RF pulses, high power

RF Power source: 5 MW Klystron

RF Gun cavity: 1.5-cell copper cavity operated at 1.3 GHz





- rf pulse lenght: **900 μs ,** repetition rate: **10 Hz**

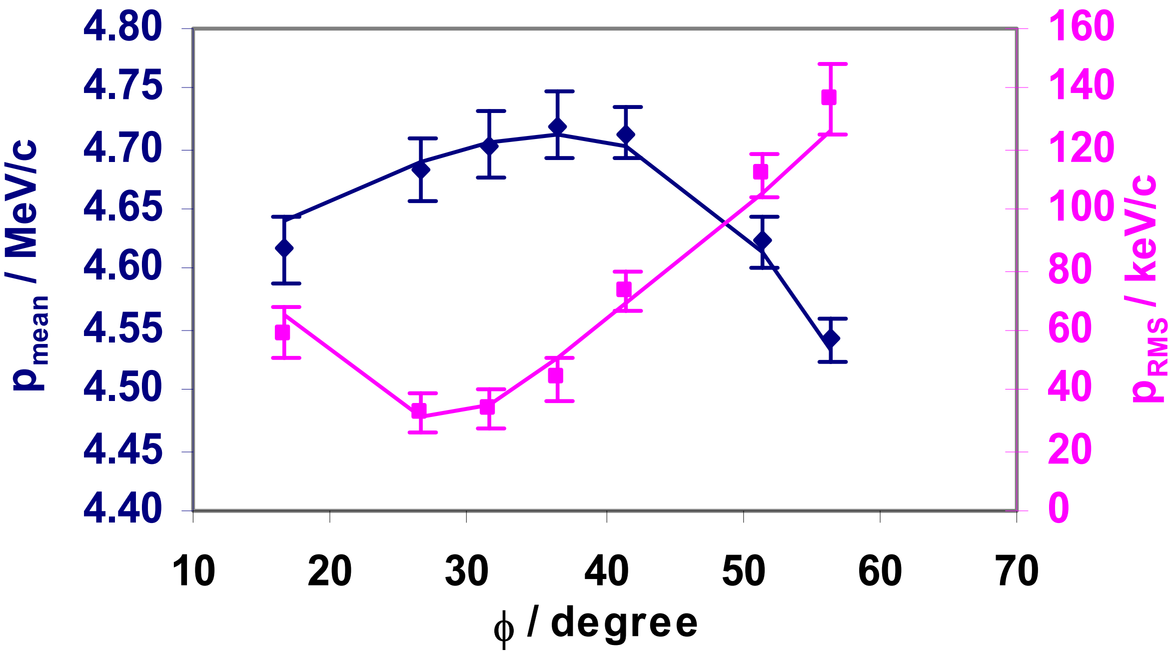
- gradient: **42 MV/m at the cathode** (~ 3 MW)

⇒ duty cycle: 0.9 %, average rf power: 27 kW

(results only limited by conditioning time)

fulfills VUV-FEL RF parameter requirements

VUV-FEL Gun: Longit. Phase Space



Q = 1 nC

max. mean momentum:

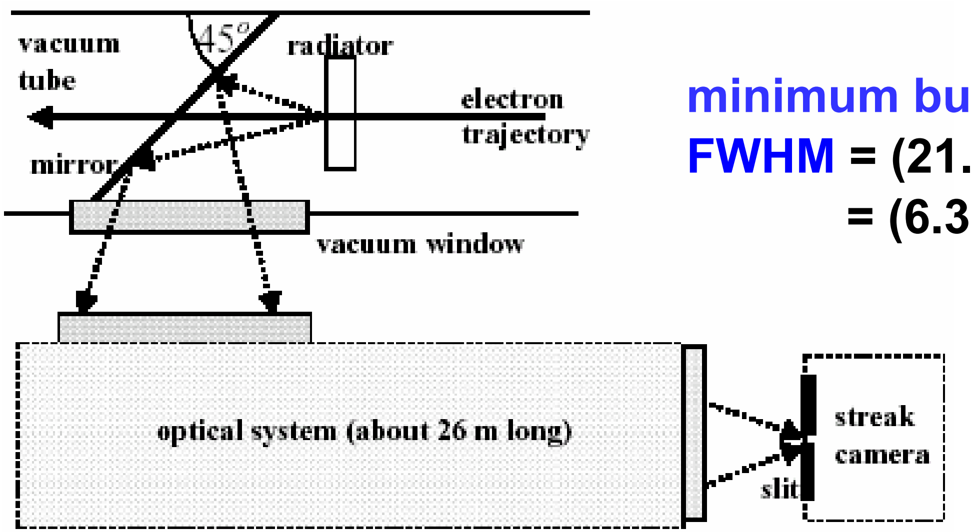
4.72 MeV/c

min. rms momentum spread:

33 keV/c

good agreement with simulations !

bunch length:

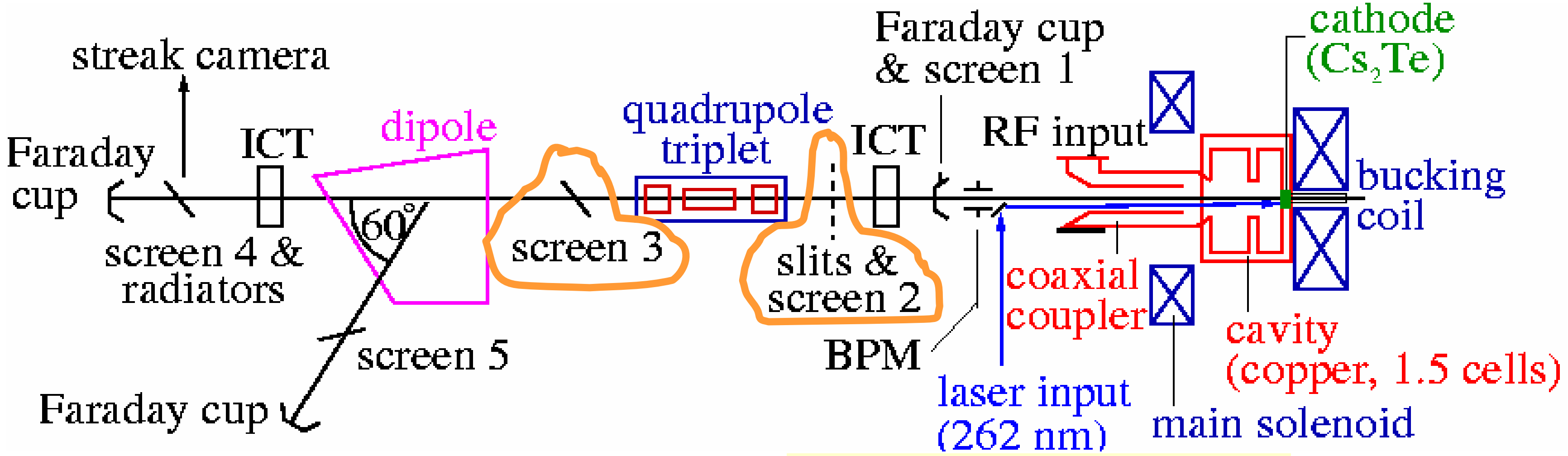


minimum bunch length:

FWHM = (21.04 ± 0.45stat ± 4.14syst) ps

= (6.31 ± 0.14stat ± 1.24syst) mm

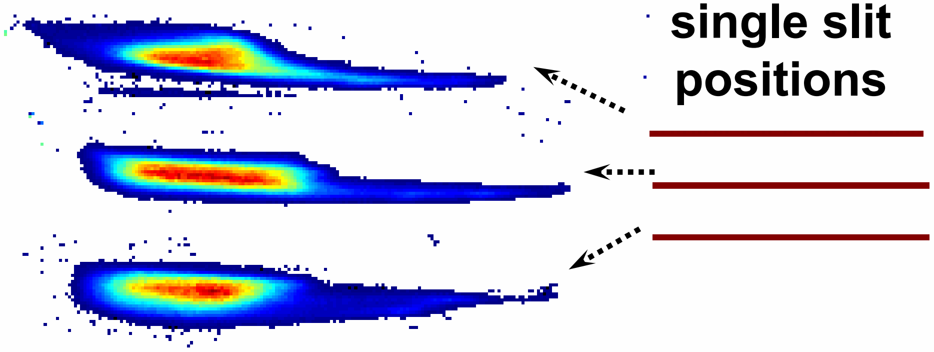
Transverse Emittance Measurements



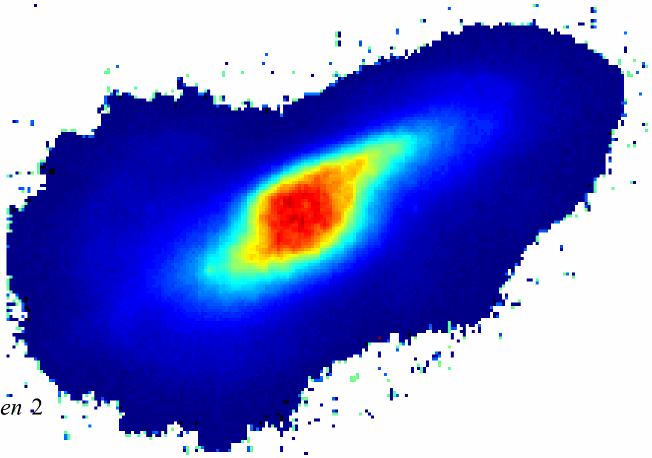
Single Slit Scan Technique

$$\varepsilon_{nx} = \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

beamlets at screen 3



beam spot at screen 2

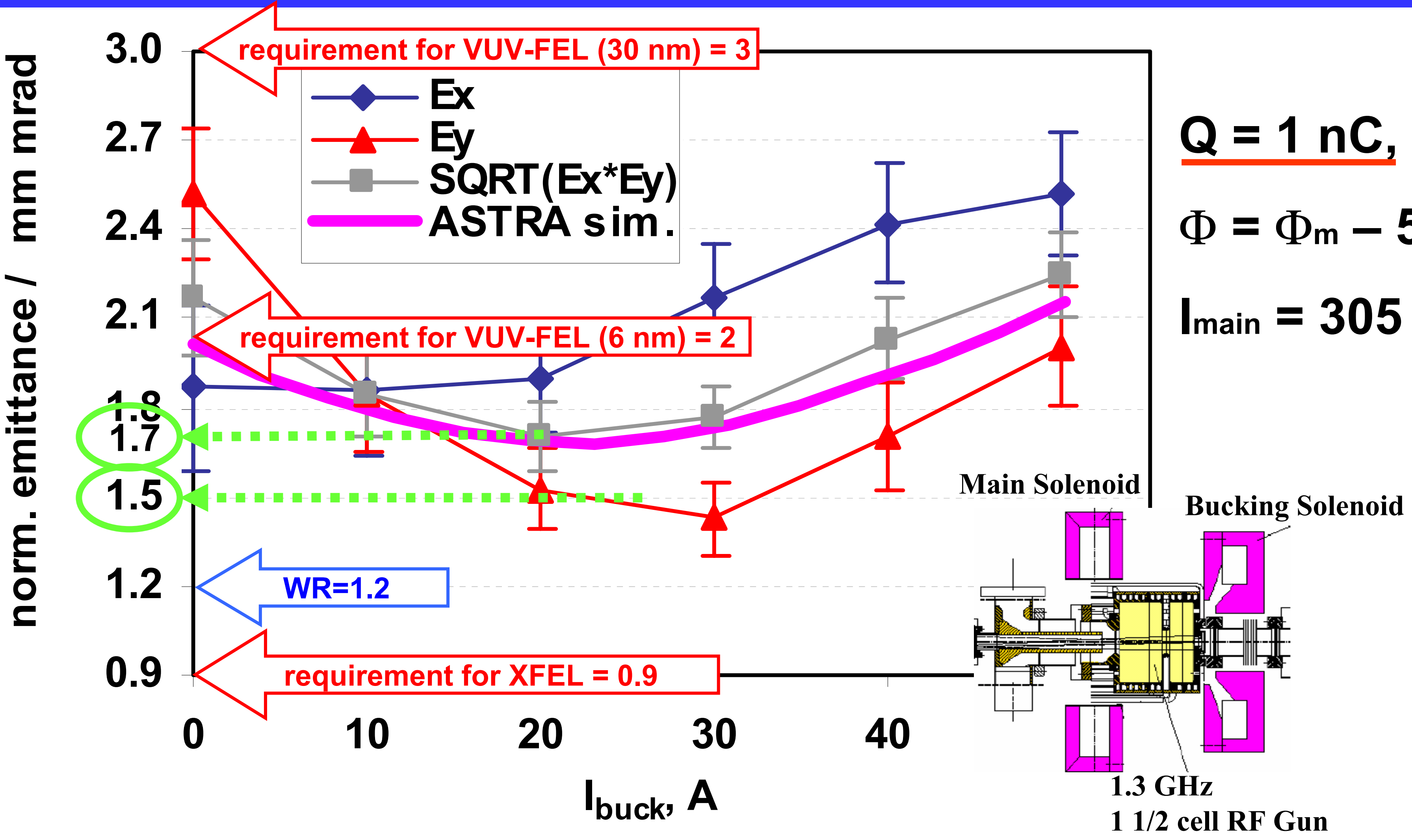


beamlet size is measured for 3 slit positions:

$$y_n = \langle Y\rangle^{screen\ 2} + n\cdot 0.7\sigma_y^{screen\ 2}$$

$$n \in \{-1,0,1\}$$

VUV-FEL Gun: Transverse Emittance



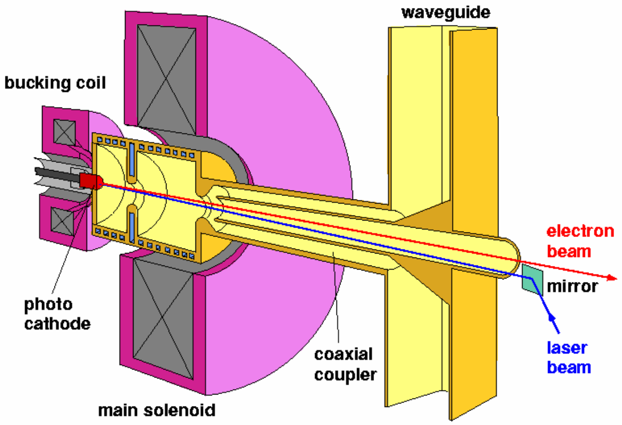
Q = 1 nC,

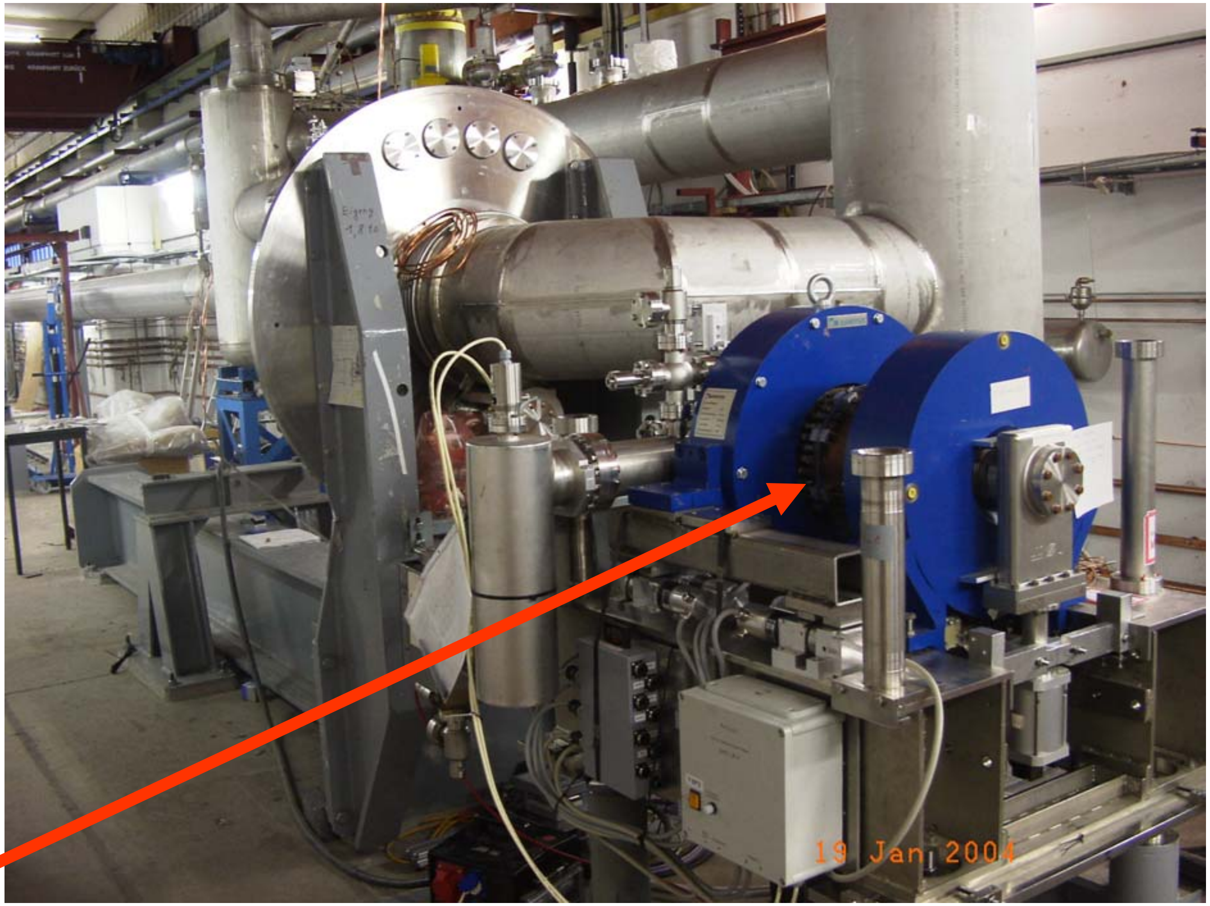
$\Phi = \Phi_m - 5°$

I_{main} = 305 A

Start-up requirement of TTF2 is clearly fulfilled !

Picture from the VUV-FEL at Hamburg





PITZ gun was installed at VUV-FEL in Jan. 2004

Prototype #1: RF Conditioning Results

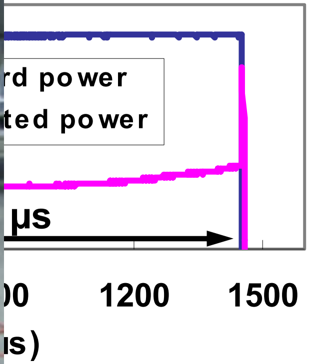
goals for the … 10 Hz

conditioning r
obtained in 20

limited by 5 MW
water cooling sy

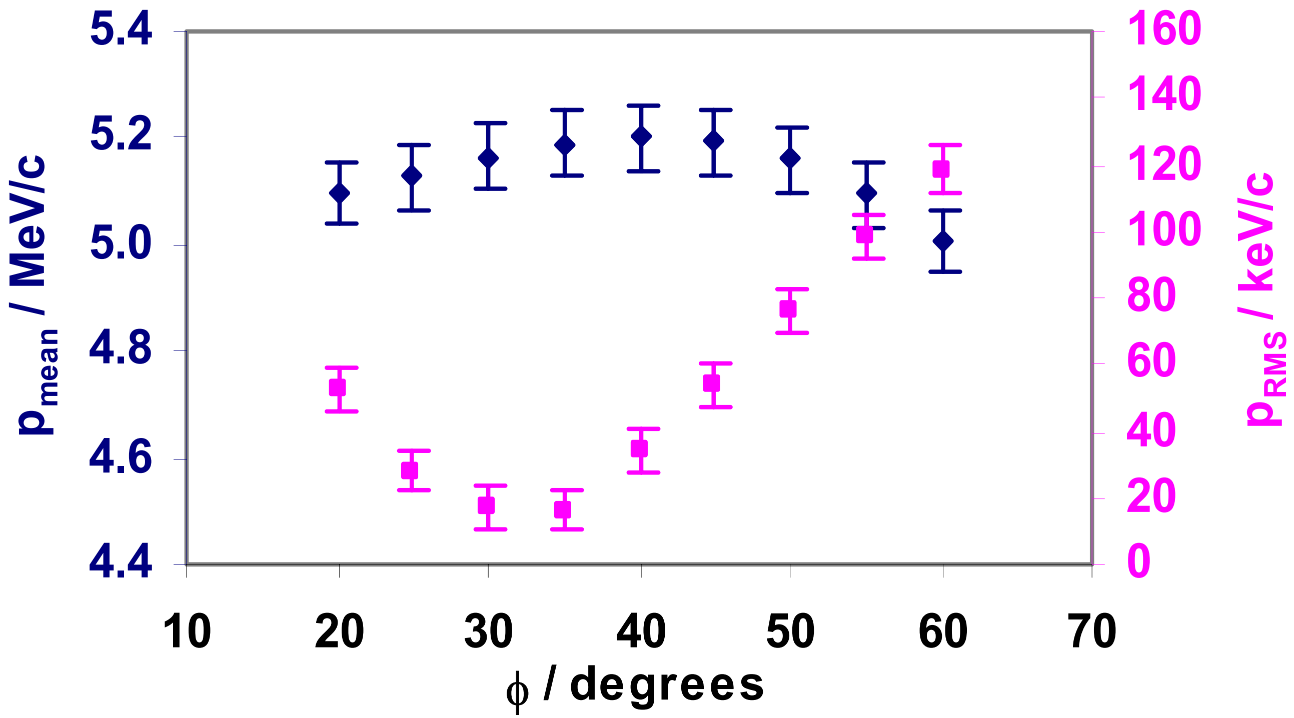
→ upgrade Dec'04
– March

10 MW klystron delivered on 19. 1. 2005



5 Hz	10 Hz
.3 ms	1.0 ms
4 MW	3 MW
26 kW	30 kW
.65 %	1.0 %

Prototype #1: Longit. Phase Space

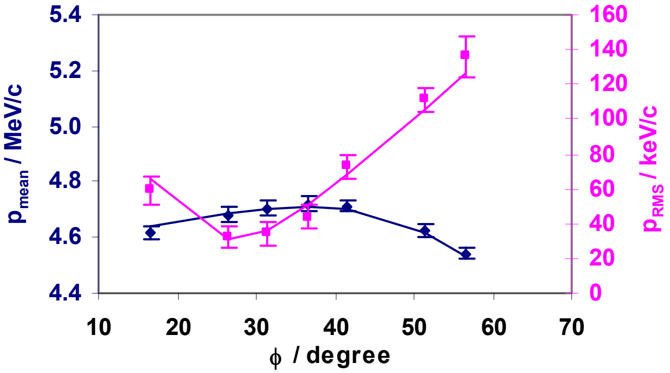


Q = 1 nC

max. mean momentum:
5.20 MeV/c
(+ 10%)

min. rms momentum spread:
16 keV/c
(- 50 %)

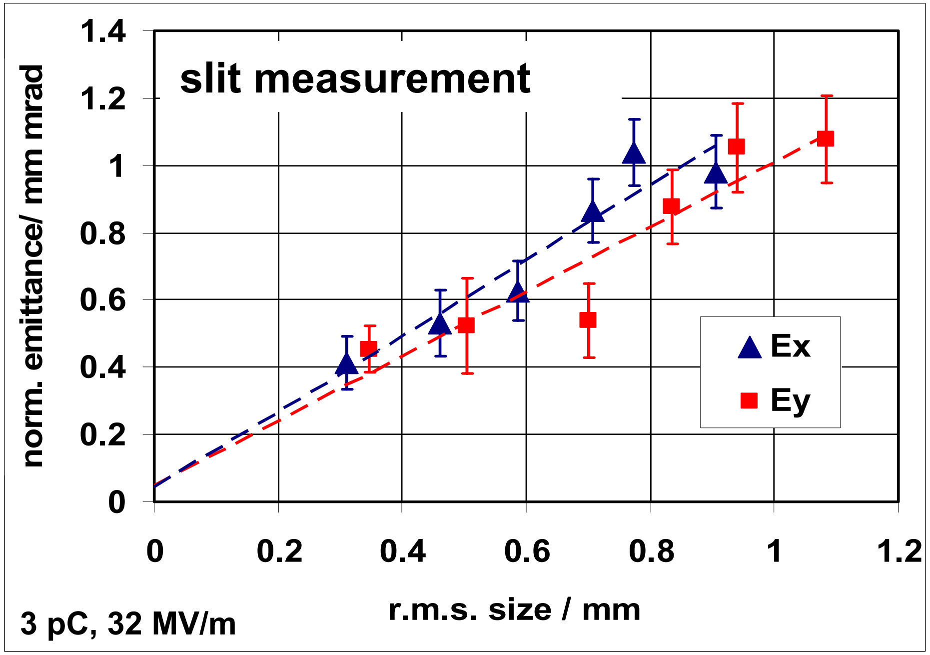
old data from VUV-FEL gun:



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

Prototype #1: Thermal Emittance

methode: $\varepsilon_{th} = \sigma\sqrt{\frac{2E_k}{3m_0c^2}}$ ⟷ $E_k = 1.5\, m_0c^2\left(\frac{d\varepsilon_{th}}{d\sigma}\right)^2$



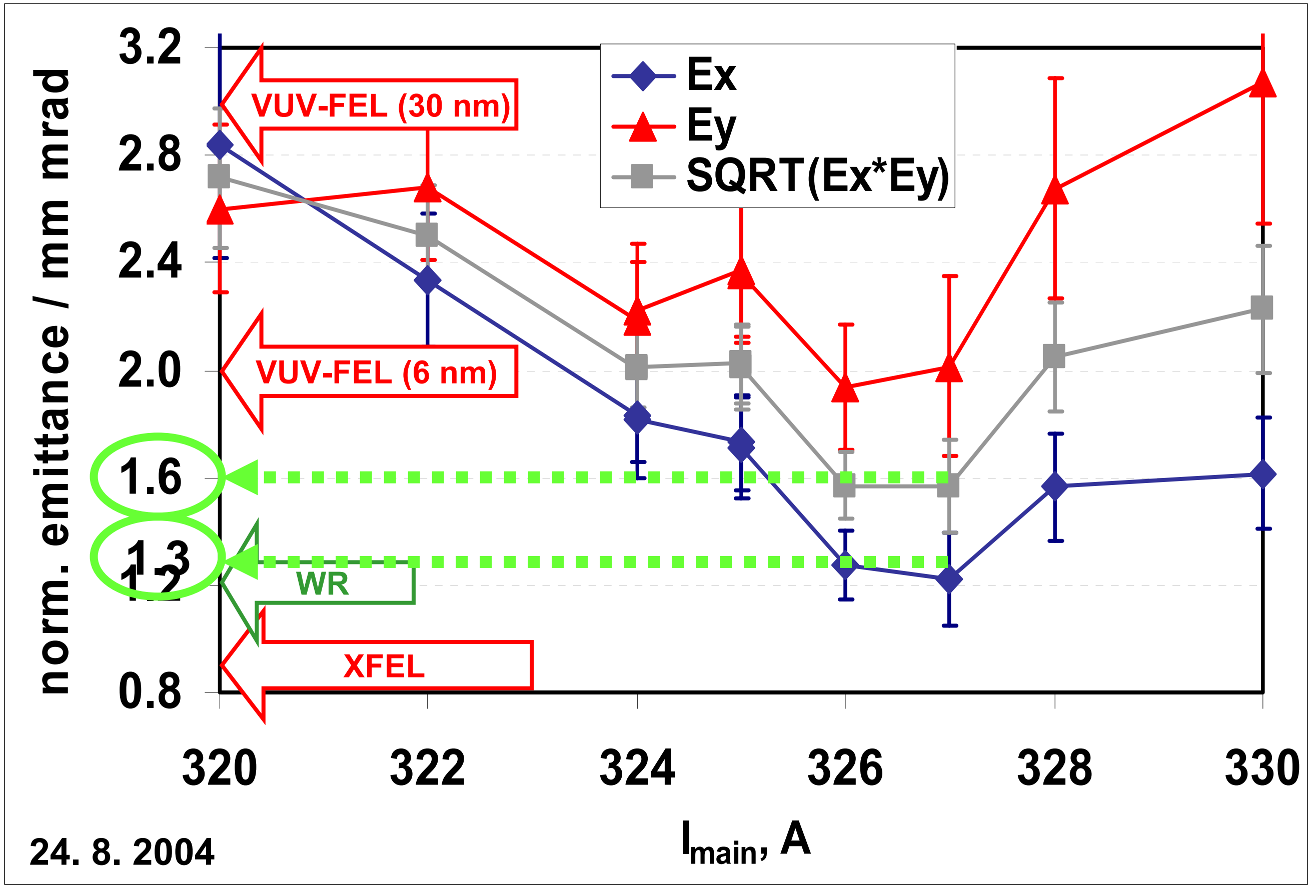
cross check with solenoid scan yielded same result:

$$E_k = 0.8 \pm 0.1\text{eV}$$

for laser r.m.s. size = 0.58 mm

$$\varepsilon_{th} \approx 0.6\ \text{mm mrad}$$

Prototype #1: Transverse Emittance



24. 8. 2004

current status !

Q = 1 nC

$\Phi = \Phi_m$

$I_{buck} = I_{main} * 0.075$

- **min. emittance and geom. average improved !**
- **still long way to go for XFEL requirements !**

PITZ 2

→ large extension of the facility and its research program

- **study emittance conservation principle:**

  (booster cavity + new diagnostics beam line + beam dynamics)

- **reach XFEL requirements: 0.9 mm mrad @ 1 nC:**

  (increased RF field on photo-cathode + improved laser system

  + beam dynamics + improved photo-cathodes)

- **study XFEL parameter space:**

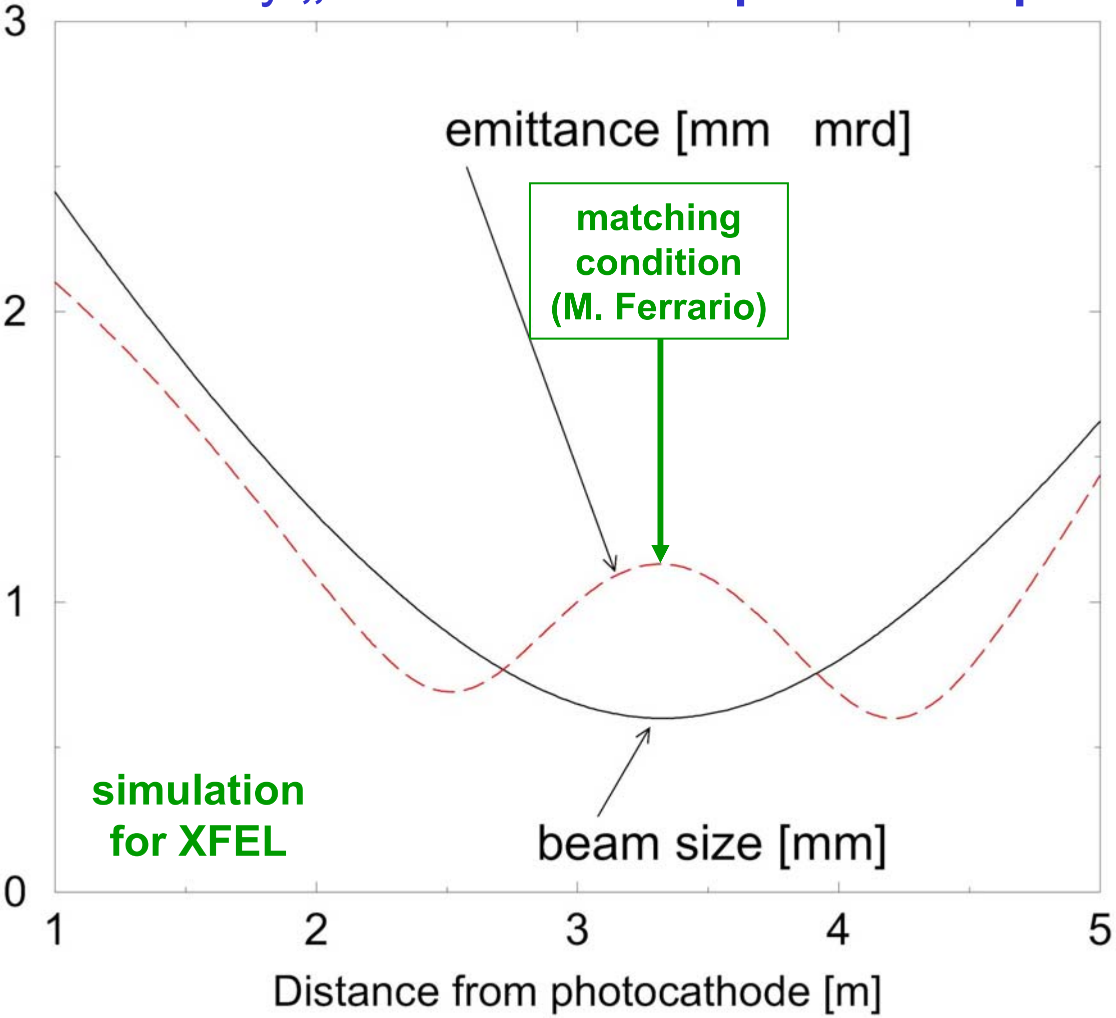
  (low charge and short bunches + vice versa)

- **operate at higher repetition rates:**

  (more cooling + new RF system + new gun cavity + diagnostics)

The Emittance Conservation Principle

Solenoid strength, drift length, and accelerating gradient of booster definded by **„invariant envelope“ technique**:



Like for LCLS:

⇒ place entrance of booster at local emit. max. and beam size min.

⇒ define accelerating gradient by:

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

γ'_{boost} = energy gain booster

σ_w = rms beam size

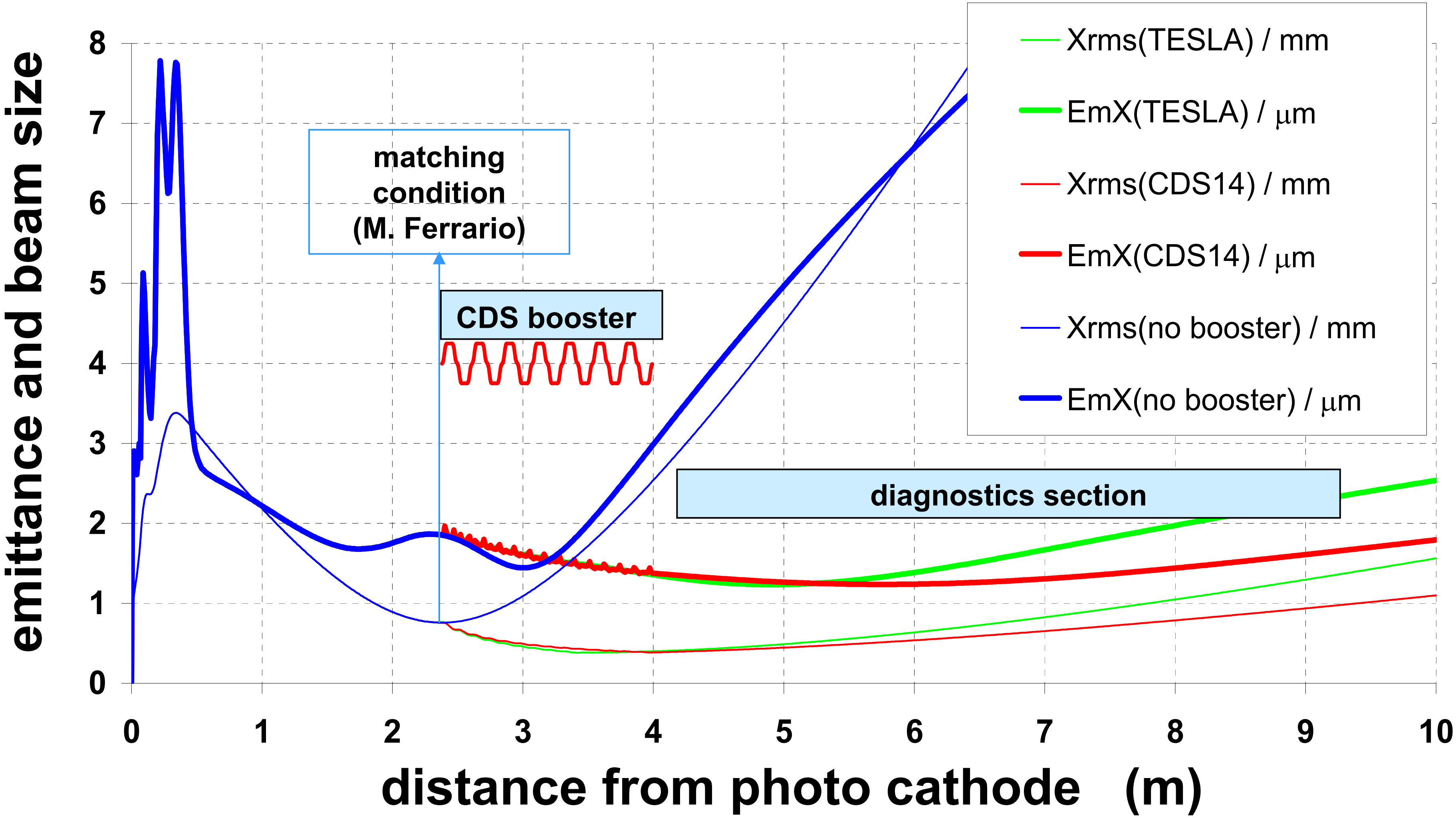
$\hat{I}$ = peak current

γ = mean beam energy

I_0 = Alvfen current

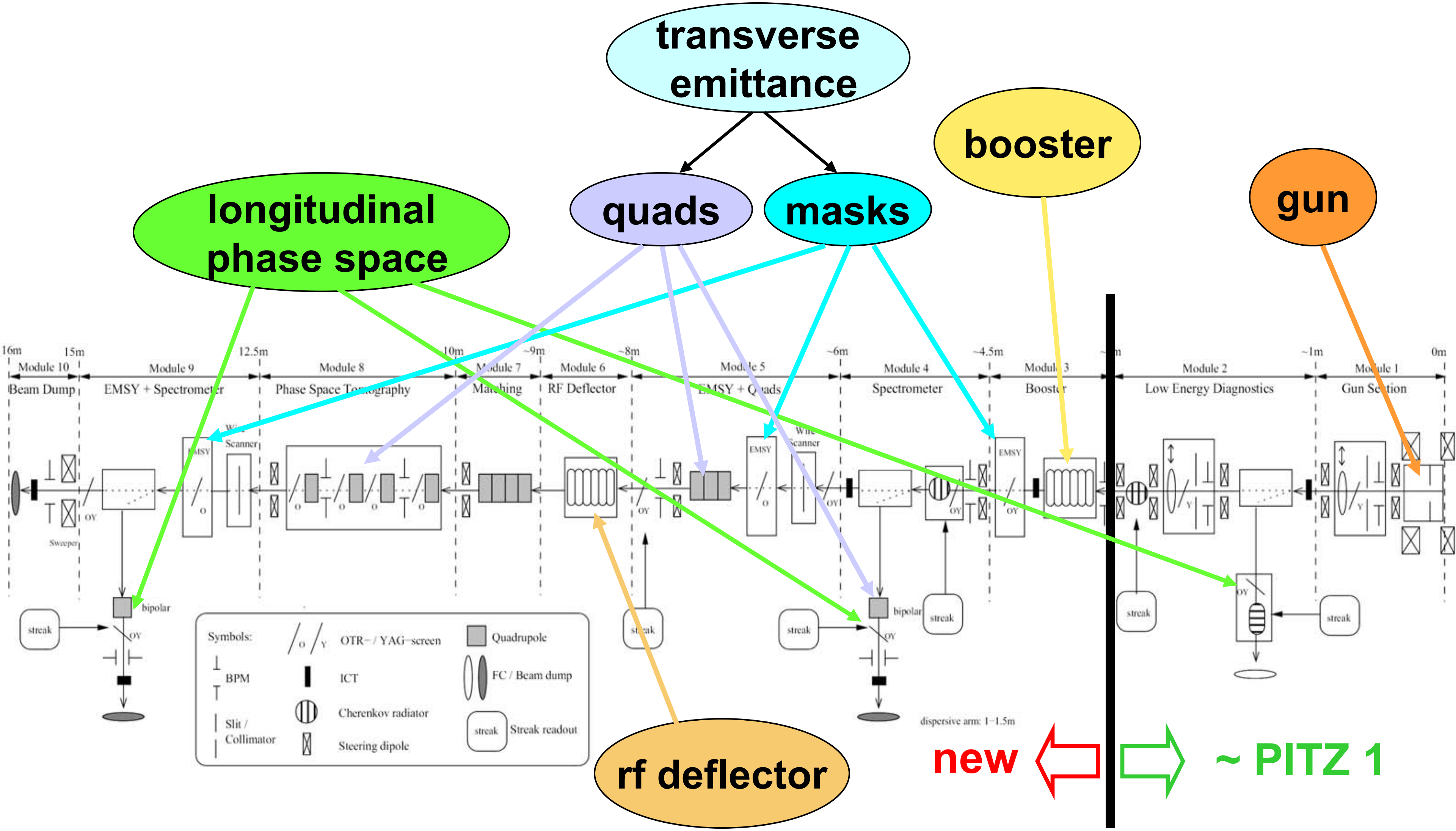
(17 kA for electrons)

ASTRA Simulation of PITZ2 (40MV/m, 20ps FWHM, 2ps rise/fall time)



⇒ **check that principle works and optimize it !**

Preliminary Layout of PITZ2



transverse emittance

quads

masks

booster

gun

longitudinal phase space

rf deflector

new

~ PITZ 1

How to reach the beam quality required for the XFEL

Goal: 0.9 mm mrad from the injector for 10 Hz, 650 μs !!

- **upgrades with ~ 40 MV/m at the cathode:**
  - improved homegenous transverse laser profile:

    remotely controllable diaphragm close to the cathode

    ⇒ ε_n ~ 1.5 mm mrad @ 1 nC
  - improved longitudinal laser profile (20 ps FWHM, 2 ps rise/fall time):

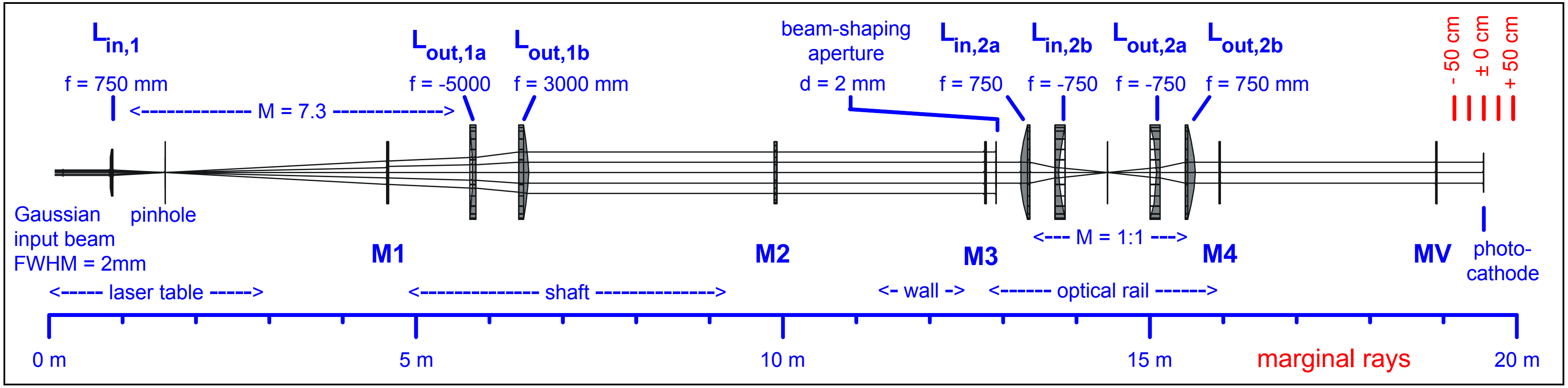
    use a broadband laser medium, solve problem of high average power, conserve stability

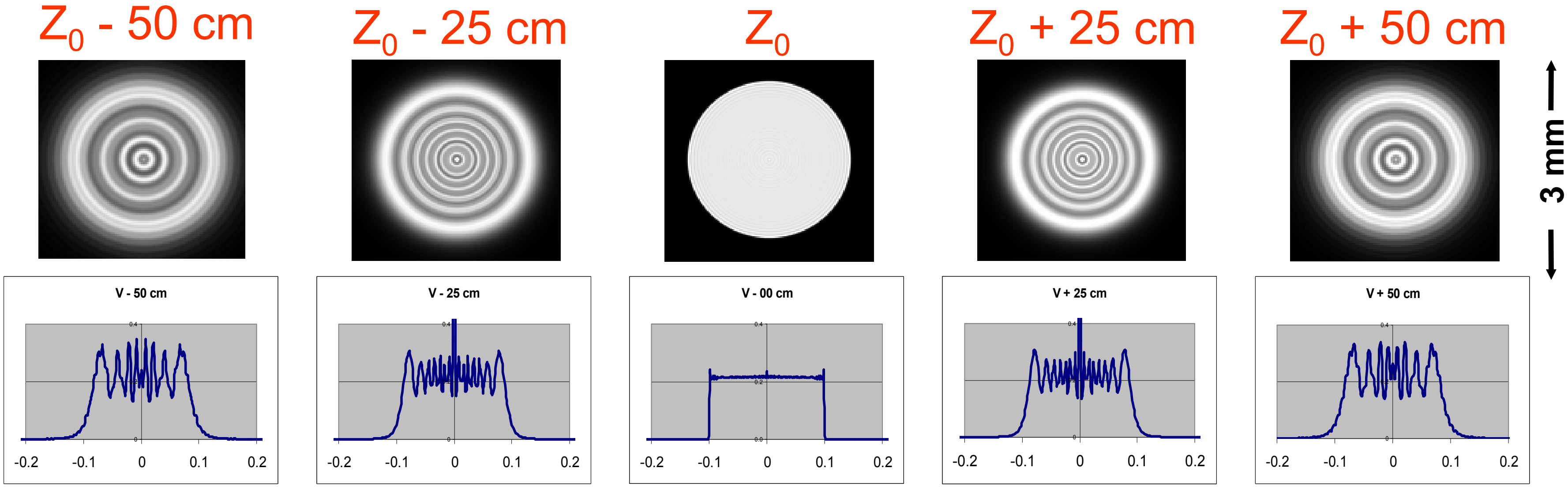
    ⇒ ε_n ~ 1.2 mm mrad @ 1 nC
- **in addition, with 60 MV/m at the cathode:**

  ⇒ ε_n ~ 0.9 mm mrad @ 1 nC

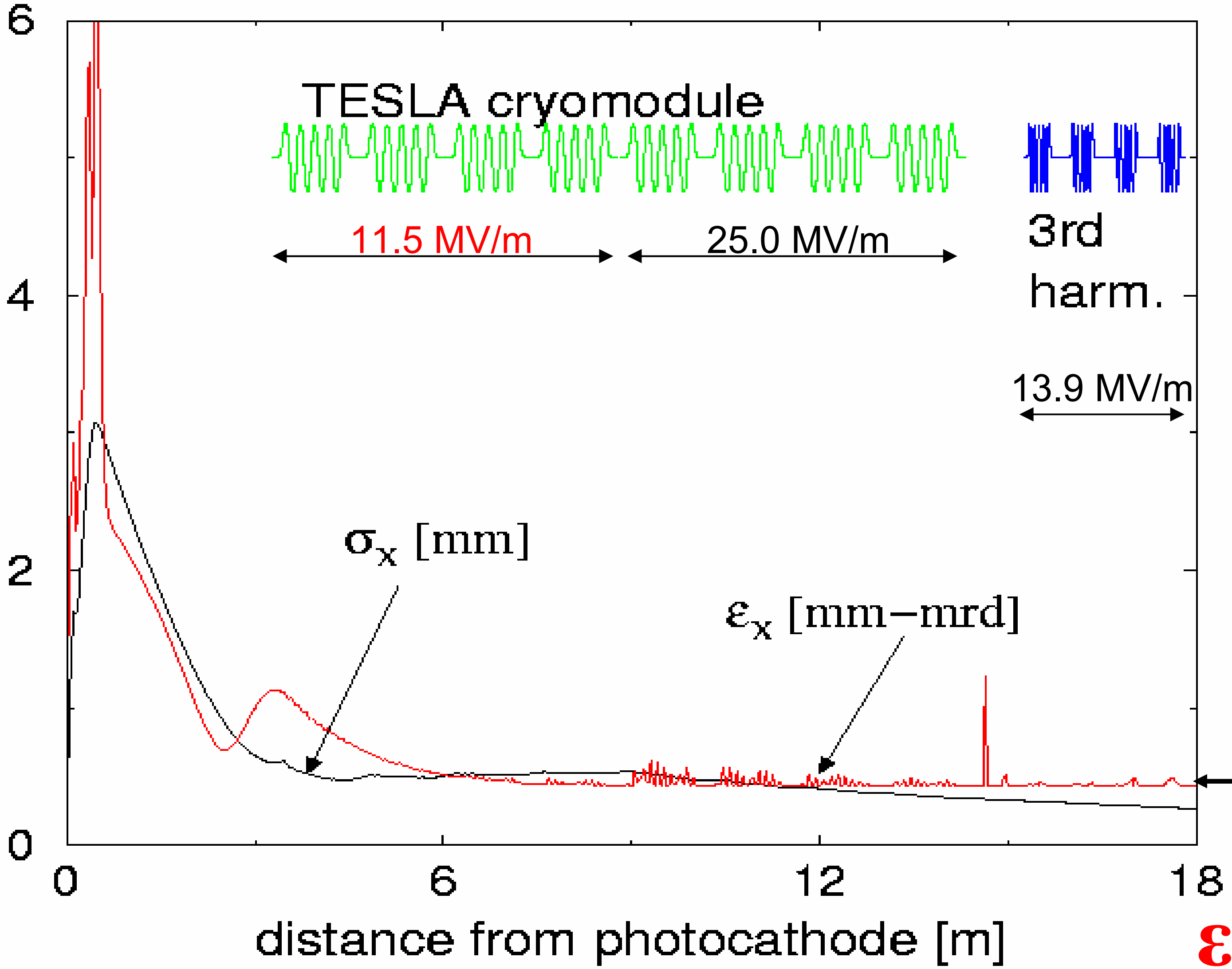
Setup for the Laser Beam Line to the Cathode

© I. Will (MBI), status: in preparation





Transverse Beam Parameters for the XFEL Injector



Courtesy of Ph. Piot, FNAL

gun param.:

rms laser spot	0.75 mm, uniform
assumed therm. emittance	0.74 mrad mm
laser pulse length	20 ps, uniform
gun acc. gradient	**60 MV/m**
injecting phase	44°

proj. emittance
≈ 0.5 mrad mm
(no th. emittance)

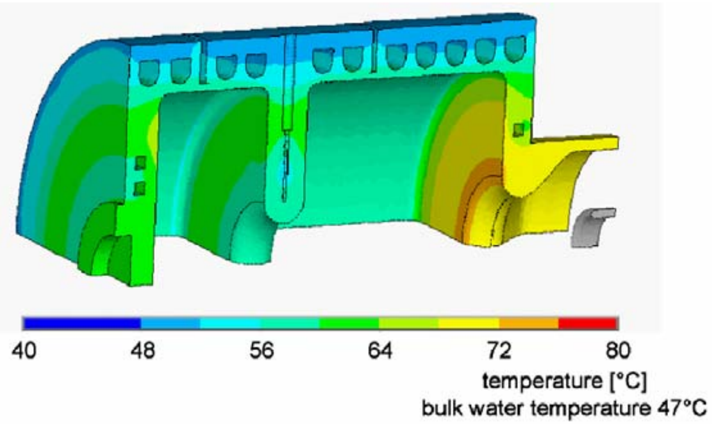
ε_n = 0.9 mrad mm

(including th. emittance)

High Gradient, High Duty Cycle

thermal calculations:

Courtesy of Frank Marhauser, BESSY

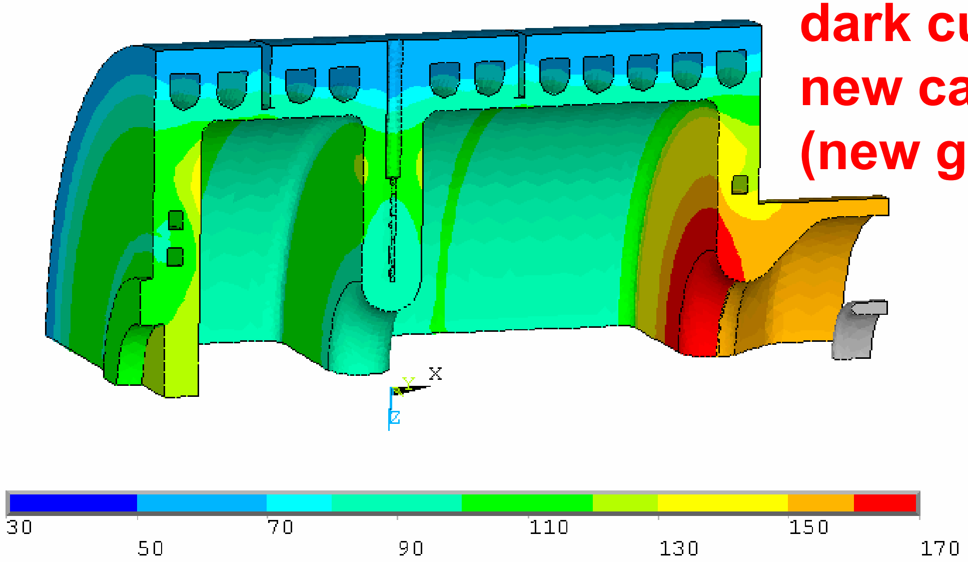


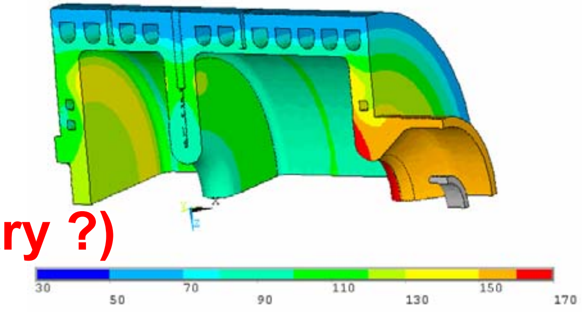
- **27 kW of average RF power: ⇒ 80°C**

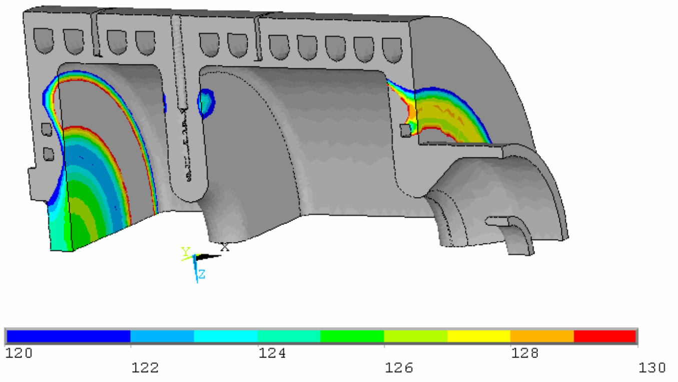
  (40MV/m, 900µs, 10 Hz) ✓done

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

  (60MV/m, 650µs, 30 Hz) ⇒vacuum,
  dark current,
  new cathodes !!!
  (new gun geometry ?)







Summary

- **different developments for achieving small emittance electron beams are ongoing worldwide (WR$|_{1\,\text{nC}}$ = 1.2 mm mrad)**

- **results at PITZ up to now:**
  - **VUV-FEL gun:**
    - **minimum normalized emittance (one plane): 1.5 mm mrad**
    - **minimum geometrical average (both planes): 1.7 mm mrad**
    - **good agreement with simulations**
  - **next gun installed at PITZ (2004):**
    - **increased rf power: <P> = 30 kW, 1 % duty cycle,**
      P_{peak} = 4 MW, rf pulse lenght = 1.3 ms
    - **beam characterization:**
      transverse emittance improved (1.3 / 1.6 mm mrad)

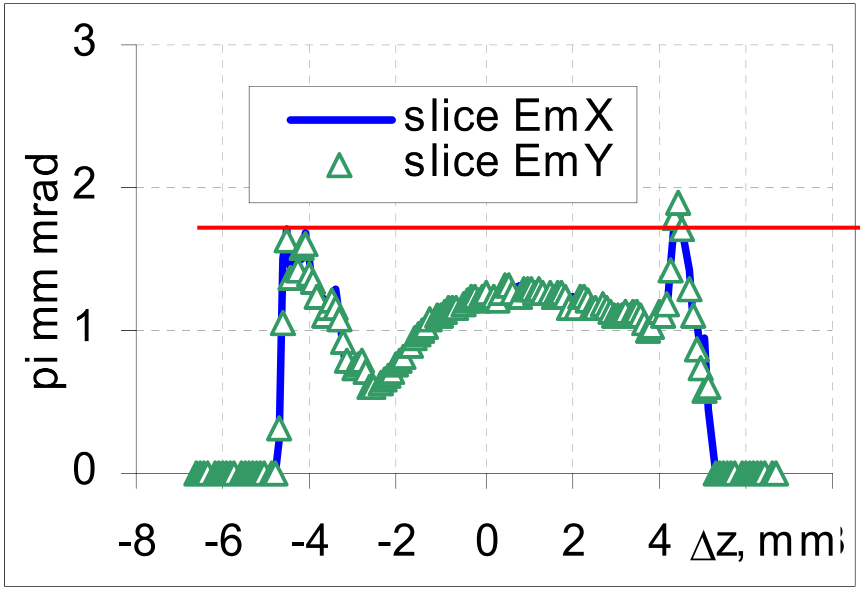
- **goal for XFEL: 0.9 mm mrad**

- **PITZ 2 will start operation in spring 2005:**
  - **further improve emittance from gun (high gradient, laser parameters)**
  - **studies on conserving small emittance to higher beam energies**

“Zugabe”:

Slice Parameters for VUV-FEL Gun

horizontal / vertical slice emittance



ASTRA simulation of
slice parameters for
z = 1.62 m (EMSY location)
I_{buck} = 20 A

projected emittance
= 1.7 mm mrad

charge density / slice energy spread