Status and Perspectives of Low Transverse Emittance Photo Cathode RF Guns

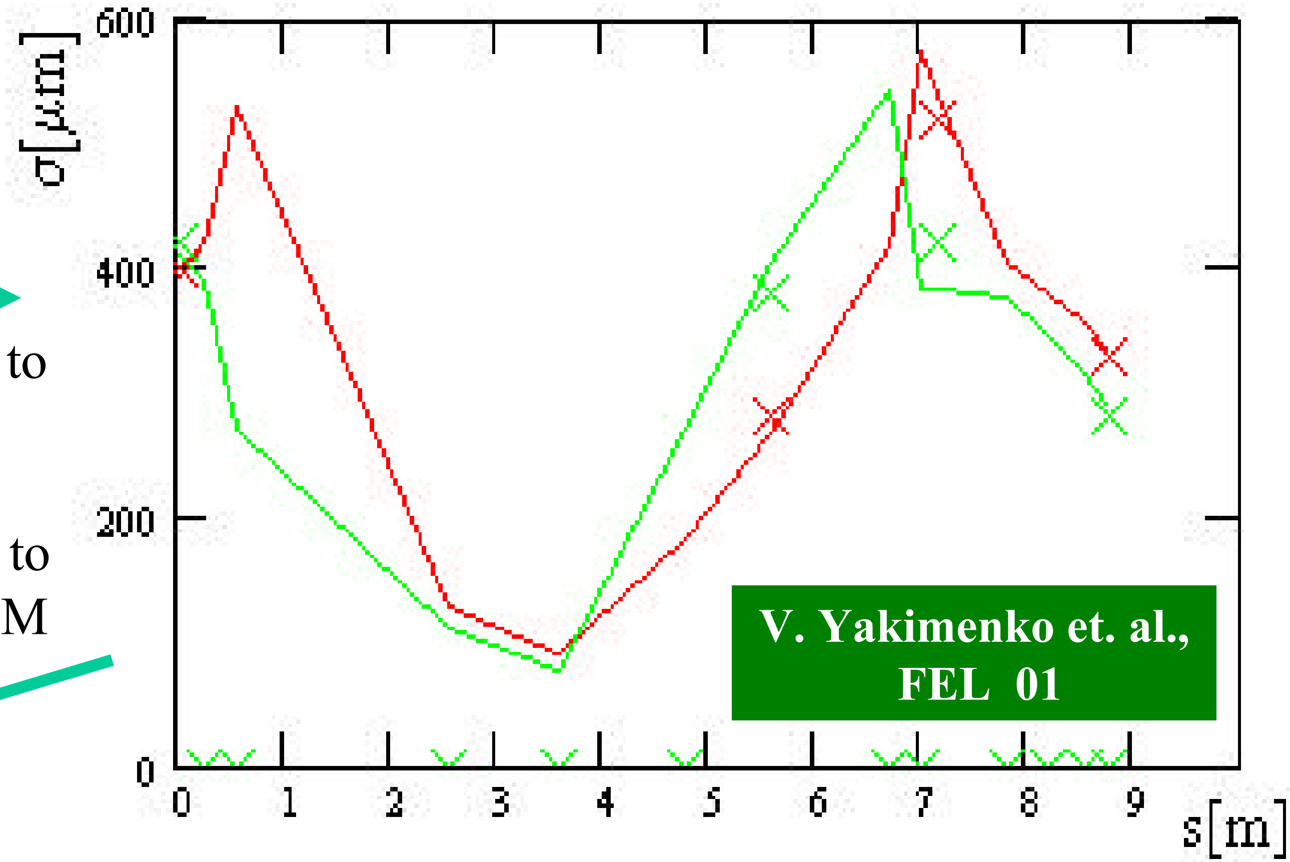
- **experimental results from**
  ATF@BNL, SDL@BNL,
  GTF@SLAC, SHI+FESTA@Japan,
  A0@FNAL, ELBE@Rossendorf
- **experimental results from PITZ@Zeuthen**
- **How to reach the beam quality required for the XFEL ?**

Frank Stephan (DESY Zeuthen),
TESLA meeting, Zeuthen, January 2004

Projected Emittance Measurements at ATF@BNL

<u>parameters:</u>
* 0.5 nC
* 110 MV/m at gun
* beam energy: 60 MeV

<u>methode:</u>
* fitting Twiss parameters to 4 subsequent beam size measurements
* transport optics adjusted to maximize beam size at BPM locations



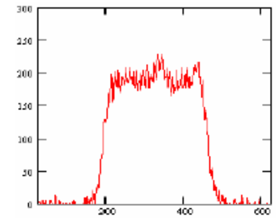
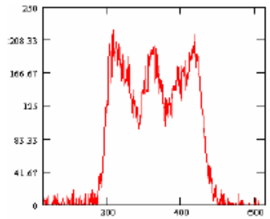
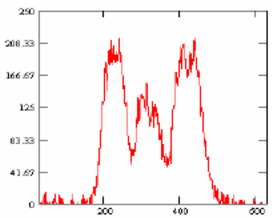
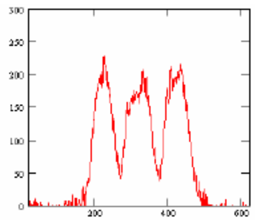
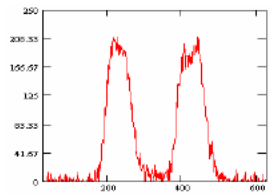
<u>fit result:</u>

ε_n = 0.8 μm for 0.5 nC, **accuracy: better than 15%**

<u>path to small emittance:</u>
check resolution limit of BPM, stability of laser and RF, BBA of beam optical elements, improve gun gradient and QE, optimize transverse laser shape and emission phase, tune beam with SASE gain at VISA

Transverse Laser Shape Studies from ATF@BNL

cylindical symmetric

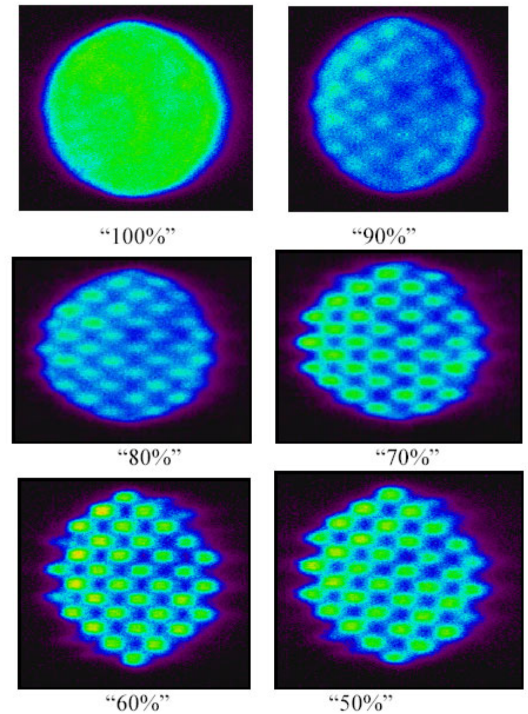






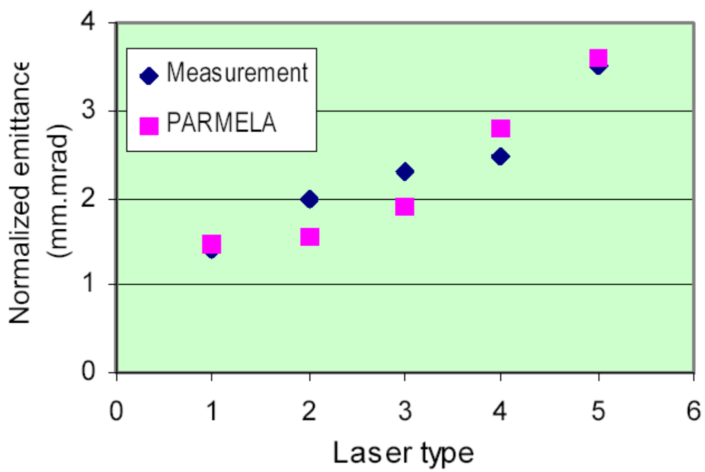
Upper left: type 1
Upper right: type 2
Middle left: type 3
Middle right: type 4
Lower left: type 5

parameters:

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

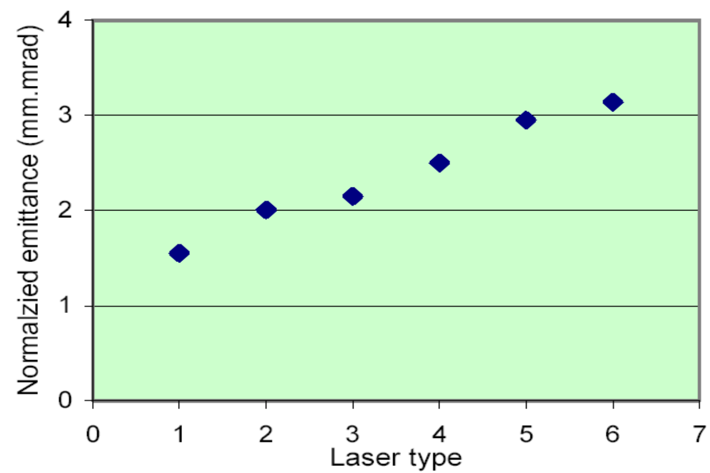
non-cylindical symmetric





additional study:

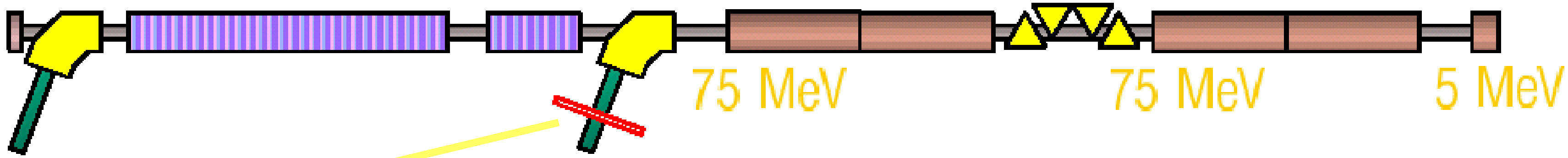
emittance vs charge ~ linear

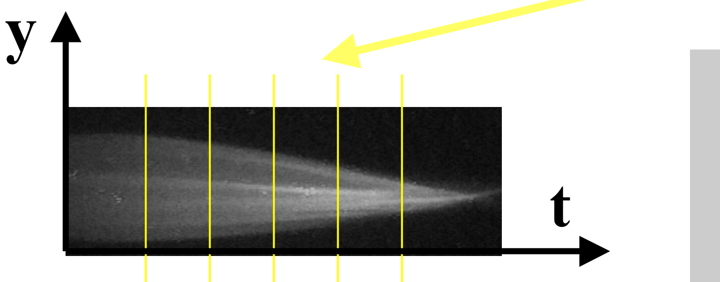


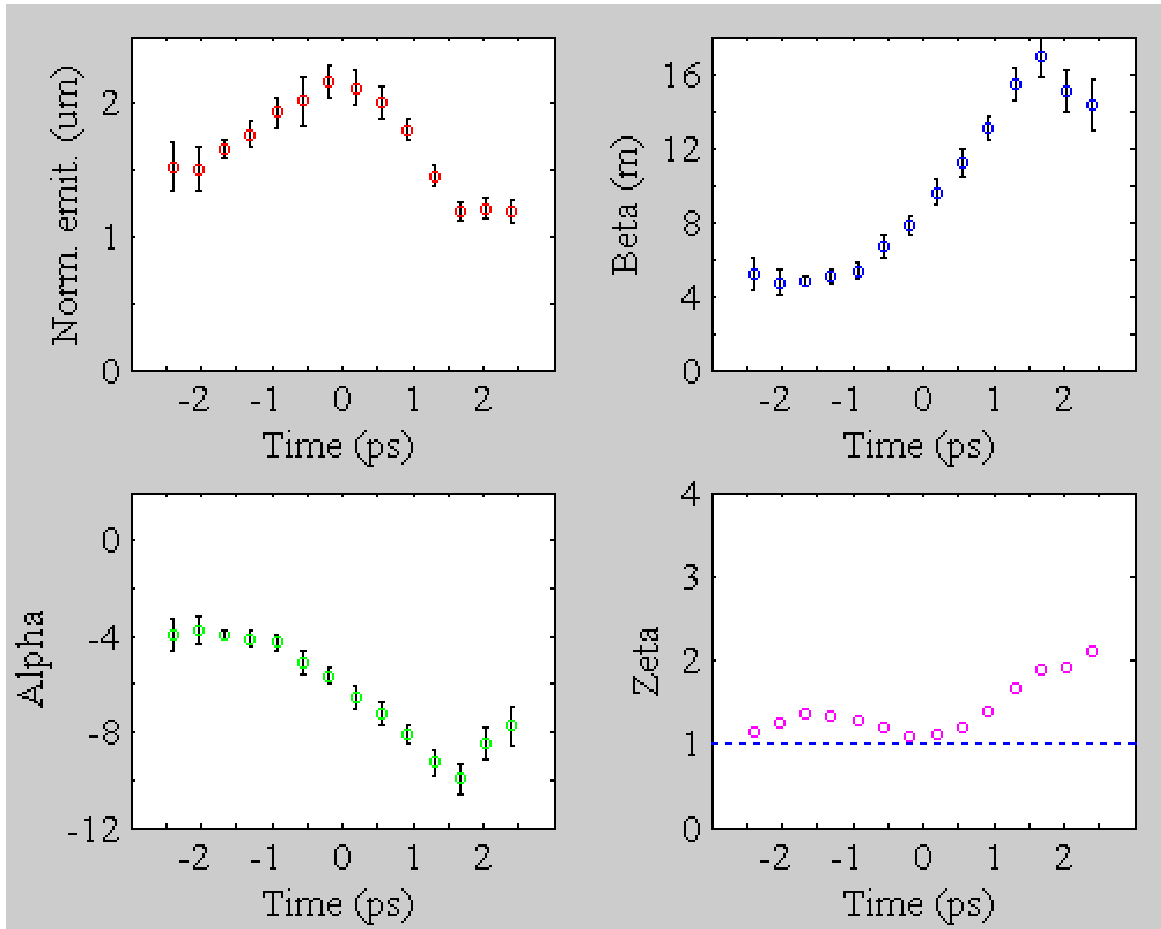
F. Zhou et. al., EPAC 02

Slice Emittance Measurements from SDL@BNL

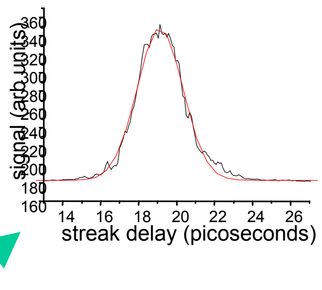
setup:







parameters:

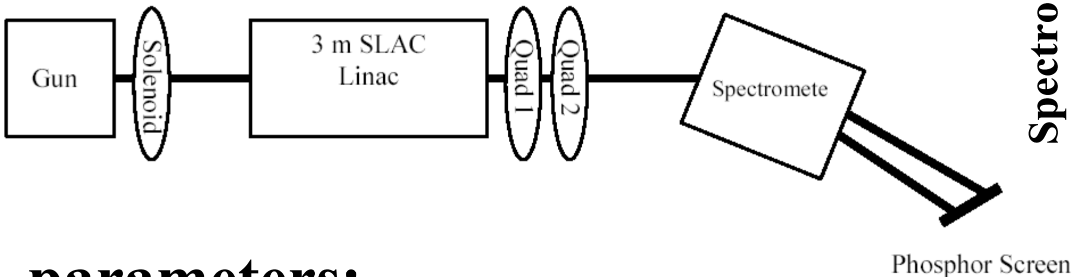


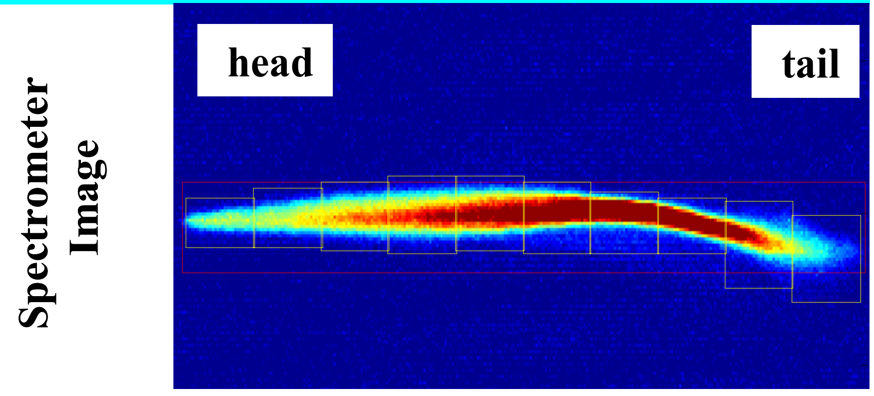
- 200 pC
- 75 MeV
- laser: 2.4 ps FWHM
- slice width ~400 fs

Courtesy of W. Graves

Slice Emittance Measurements from GTF@SLAC

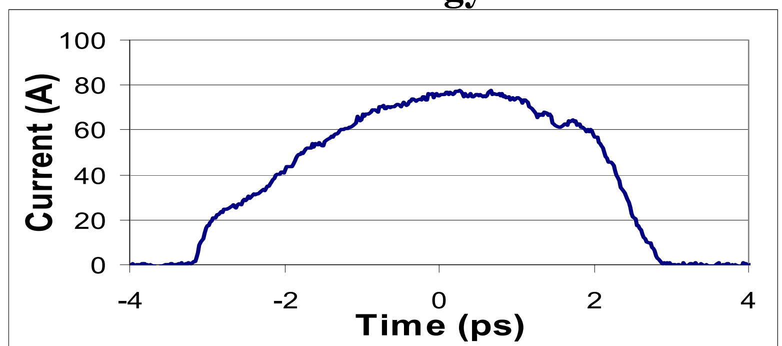
setup:

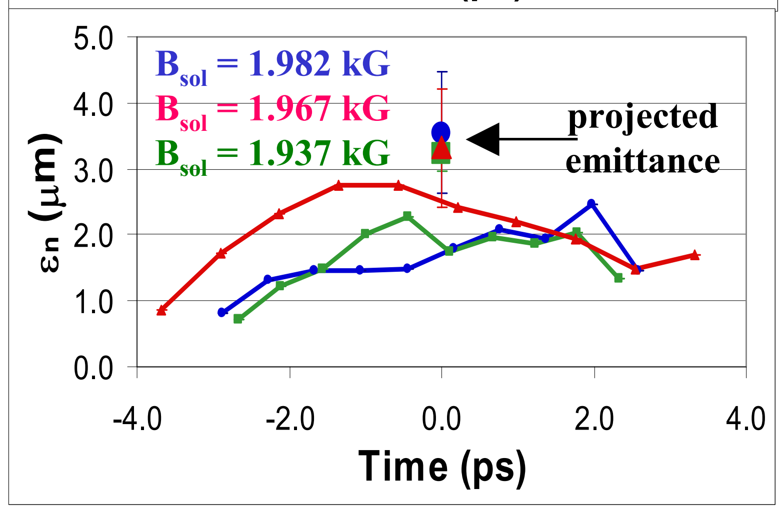




parameters:

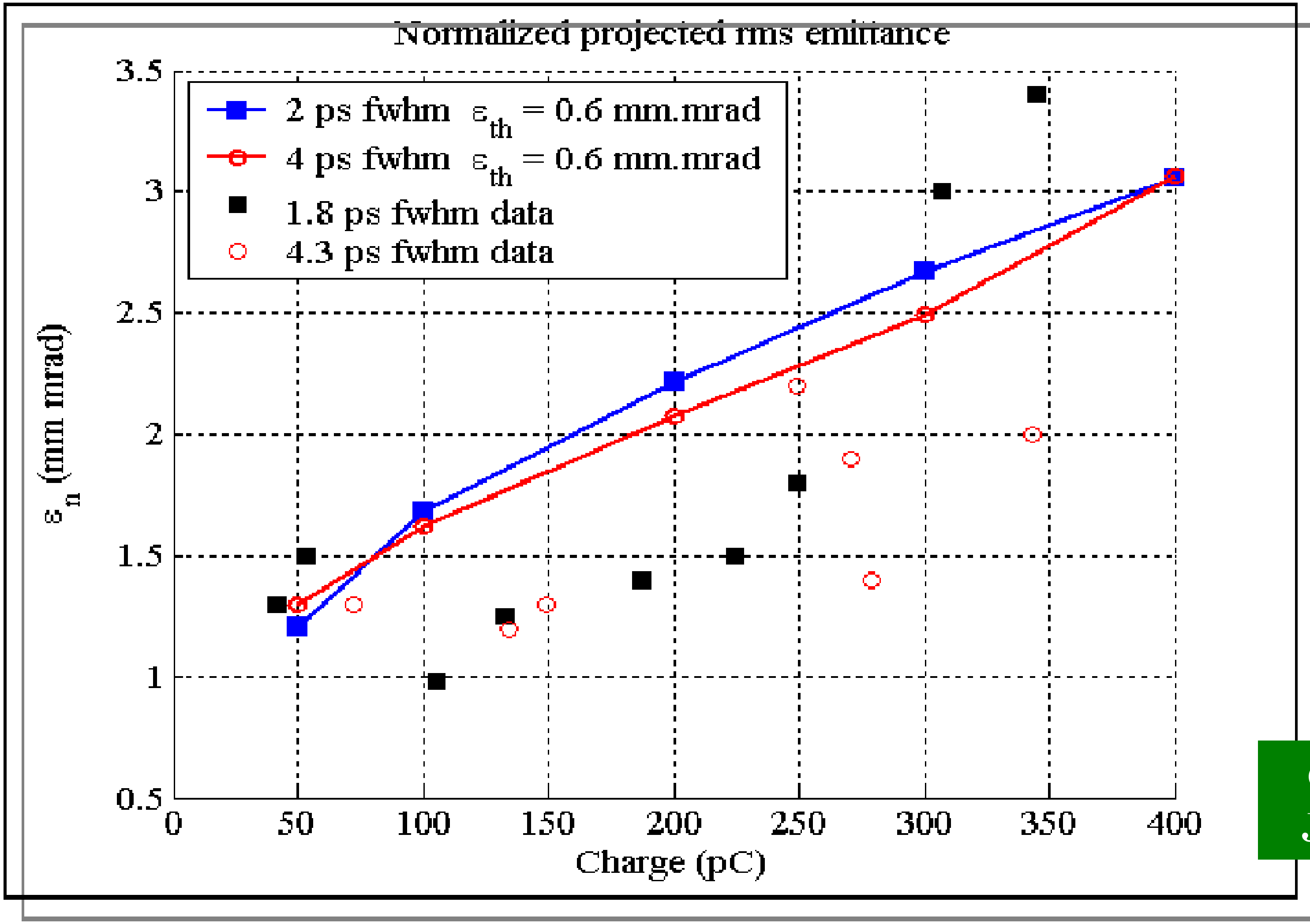
- 300 pC
- laser: 1.8 ps FWHM
  2 mm diameter on cathode
- phase: 30º from zero crossing
- slice width 550-750 fs
- beam size: signal cut at 5% of max.





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

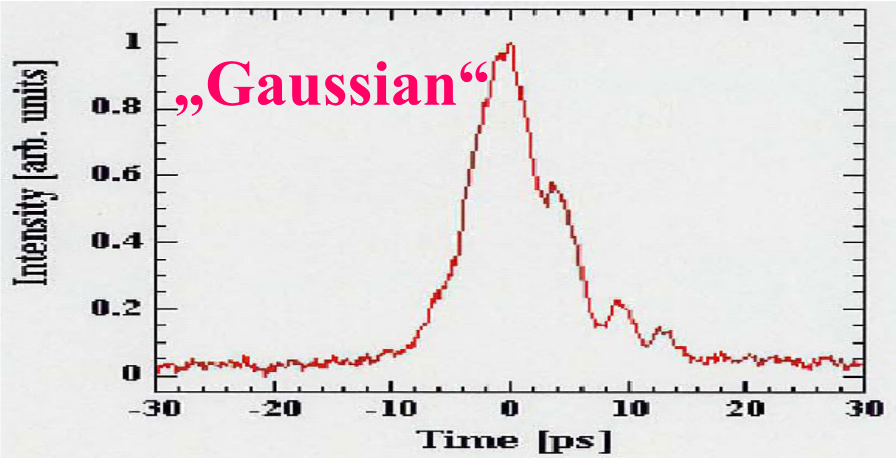
Projected Emittance vs Charge from GTF@SLAC

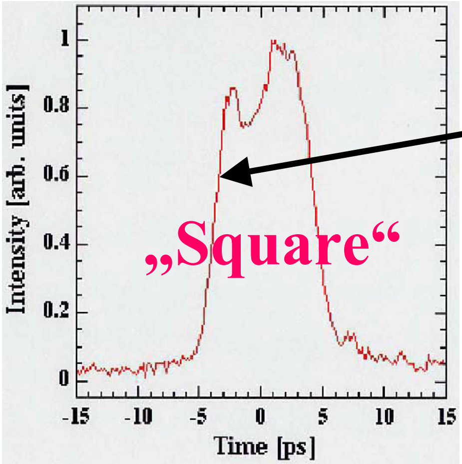


Courtesy of J. Schmerge

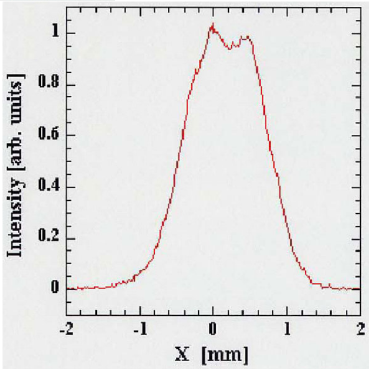
WR on Emittance from SHI+FESTA@Japan

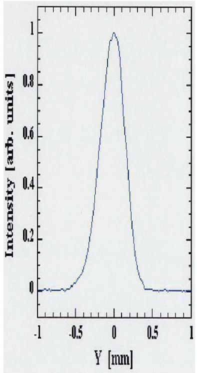
- 1.6 cell S-band gun (→ 4 MeV) + 70 cm SW linac (→ 14 MeV)
- Ti:Saphire laser system (→ 50 fs long pulses at 800 nm) + pulse shaping (e.g. gratings + liquid crystal spatial light modulator)
- temporal shape of laser pulses: (x-ray streak camera, resolution: ~2 ps)





- transverse laser distributions: (cathode)



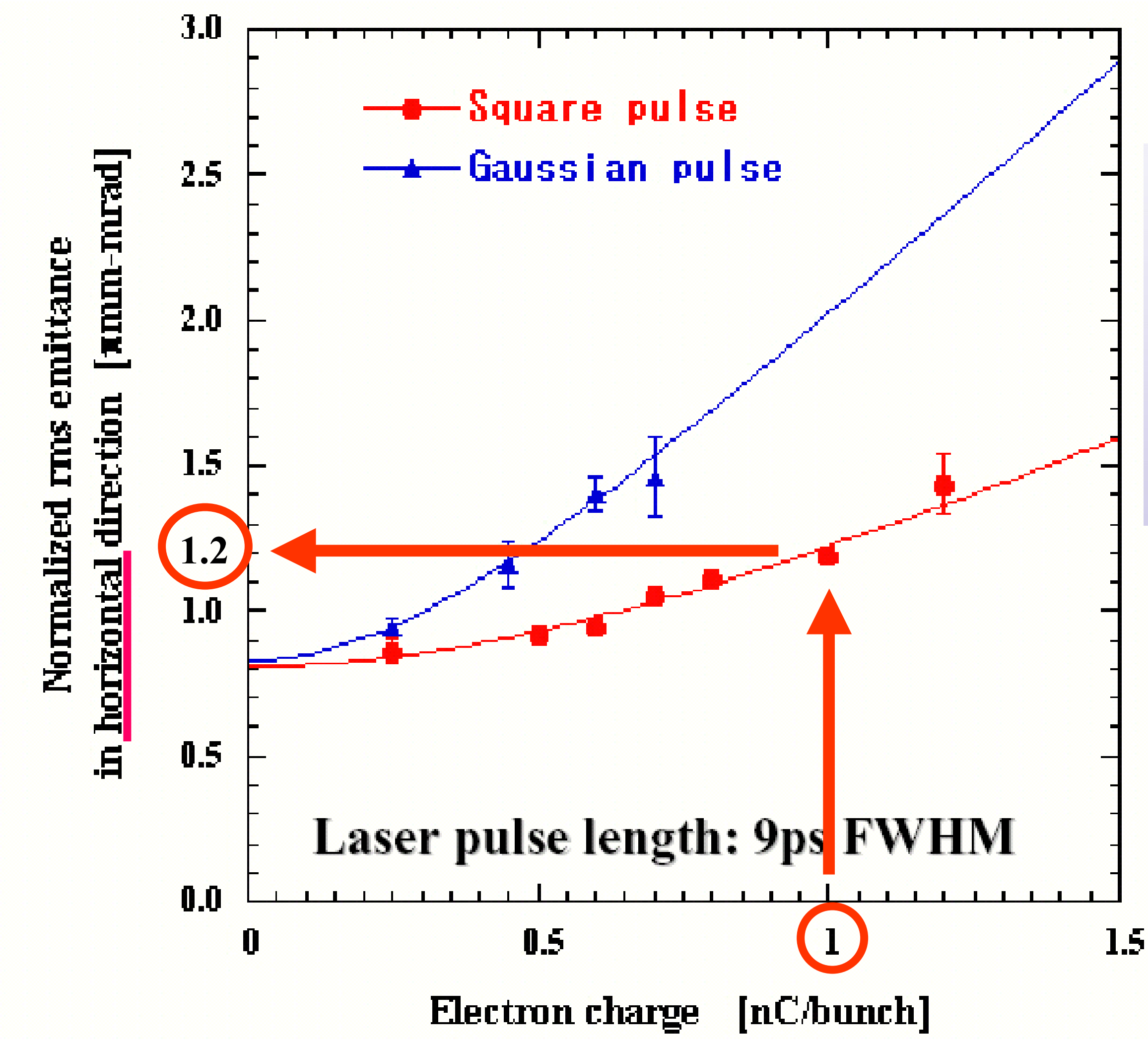


F. Sakai et. al., ICFA workshop 2002, SPring8

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)	1.85±0.13	0.83±0.05
Square (9ps)	0.92±0.05	0.81±0.03

For 1 nC:

$\varepsilon_n \approx 1.2\ \pi$ mm mrad

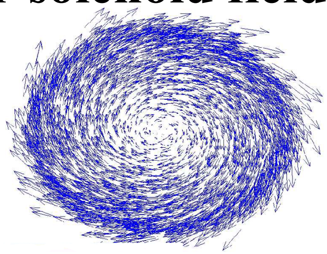
F. Sakai et. al.,
ICFA workshop 2002, SPring8

Measurements at FNPL(A0)@FNAL

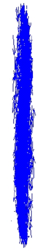
Courtesy of Ph. Piot et. al.

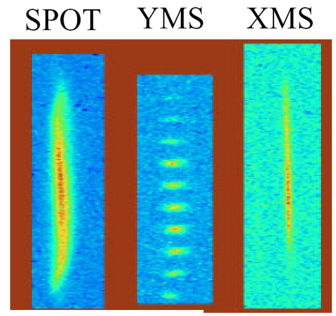
flat beam production:

after solenoid field:



after skew quads:



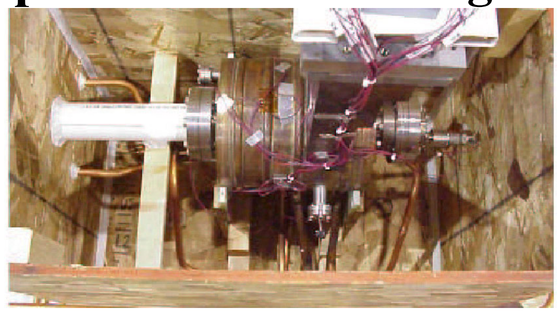


proof-of-principle experiment done, measured: $\dfrac{\varepsilon_y}{\varepsilon_x} = 45/0.9 \simeq 50$

→ now working for ratio > 100

towards polarized electrons:

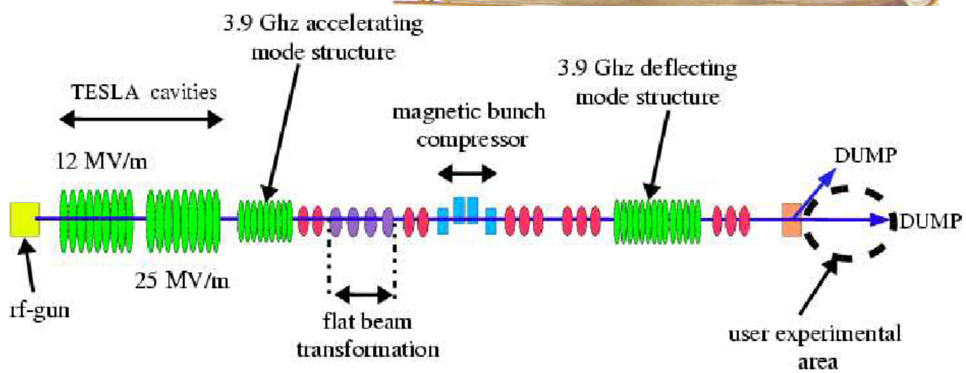
vacuum !! →crogenic operated 1 ½ cell Cu gun



also working on e.g. plasma-wakefield acc., laser-based acceleration (needs E upgrade)

NEXT:

- energy upgrade
- \+ 3.9GHz accelerating structure
- \+ 3.9 GHz deflecting cavity



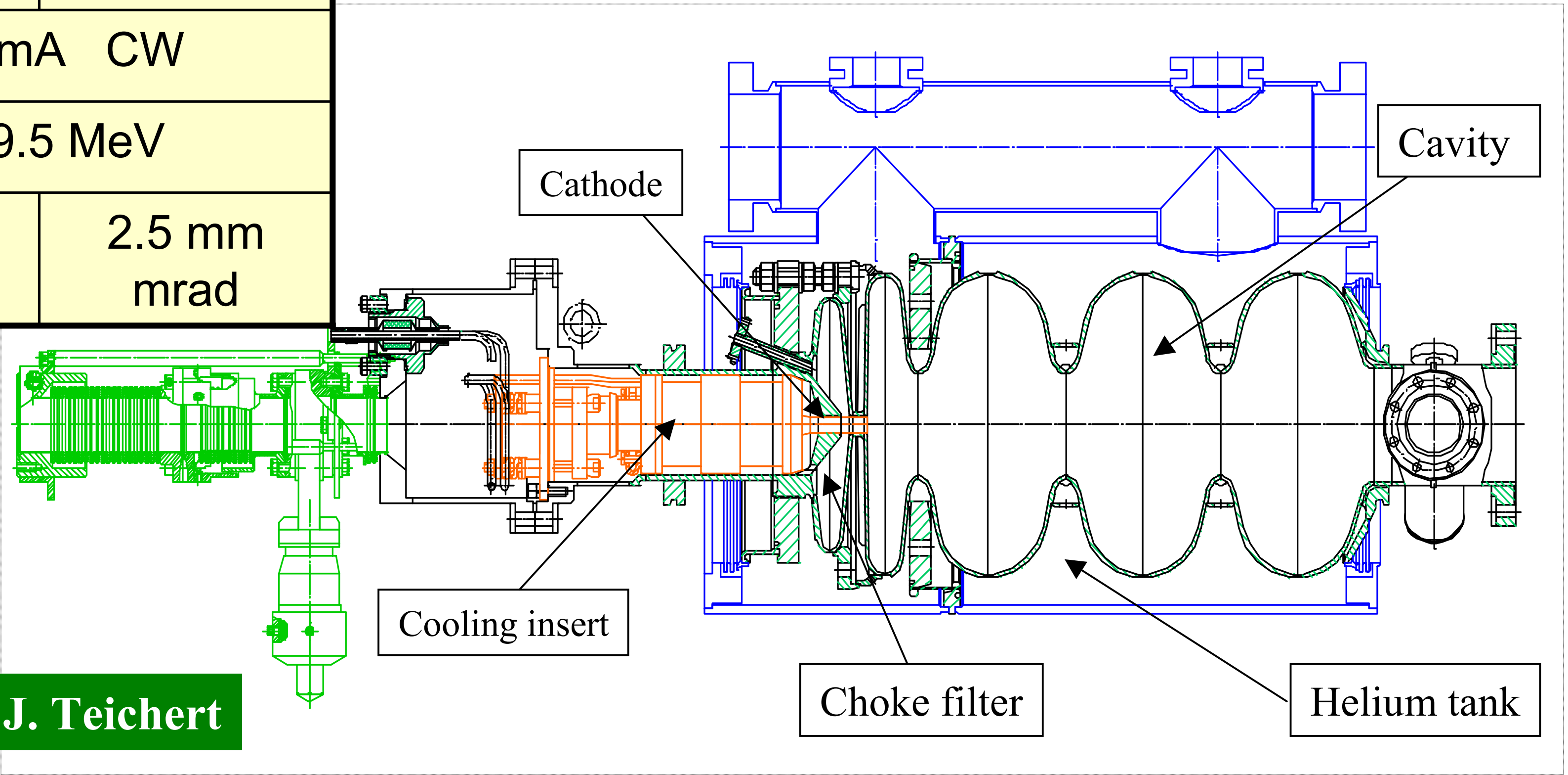
SC RF Gun Development at ELBE@Rossendorf

1.3 GHz, 10 kW half cell & 3 TESLA cells $E_{z,max}$ = 33 MV/m (1/2 cell) = 50 MV/m (T cells)	
77 pC	1 nC
I = 1 mA CW	
E = 9.5 MeV	
0.5 mm mrad	2.5 mm mrad

(without th. emit.)

Collaboration: BESSY, MBI, TJNAF, Univerity of Peking, BINP, DESY, ACCEL, TU Dresden

- **first operation of a SRF photo gun (1/2 cell) in 2002:**
  → measured current, energy + emittance @ ~1 pC
- **start of the 3+1/2 cell project in 2004:**

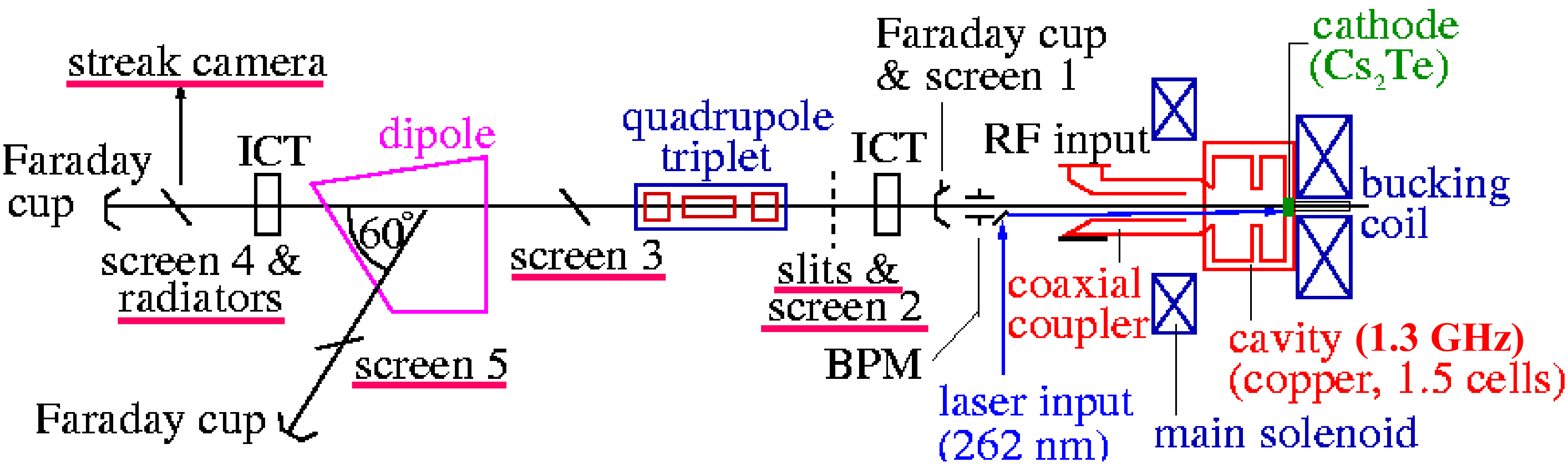


Courtesy of J. Teichert

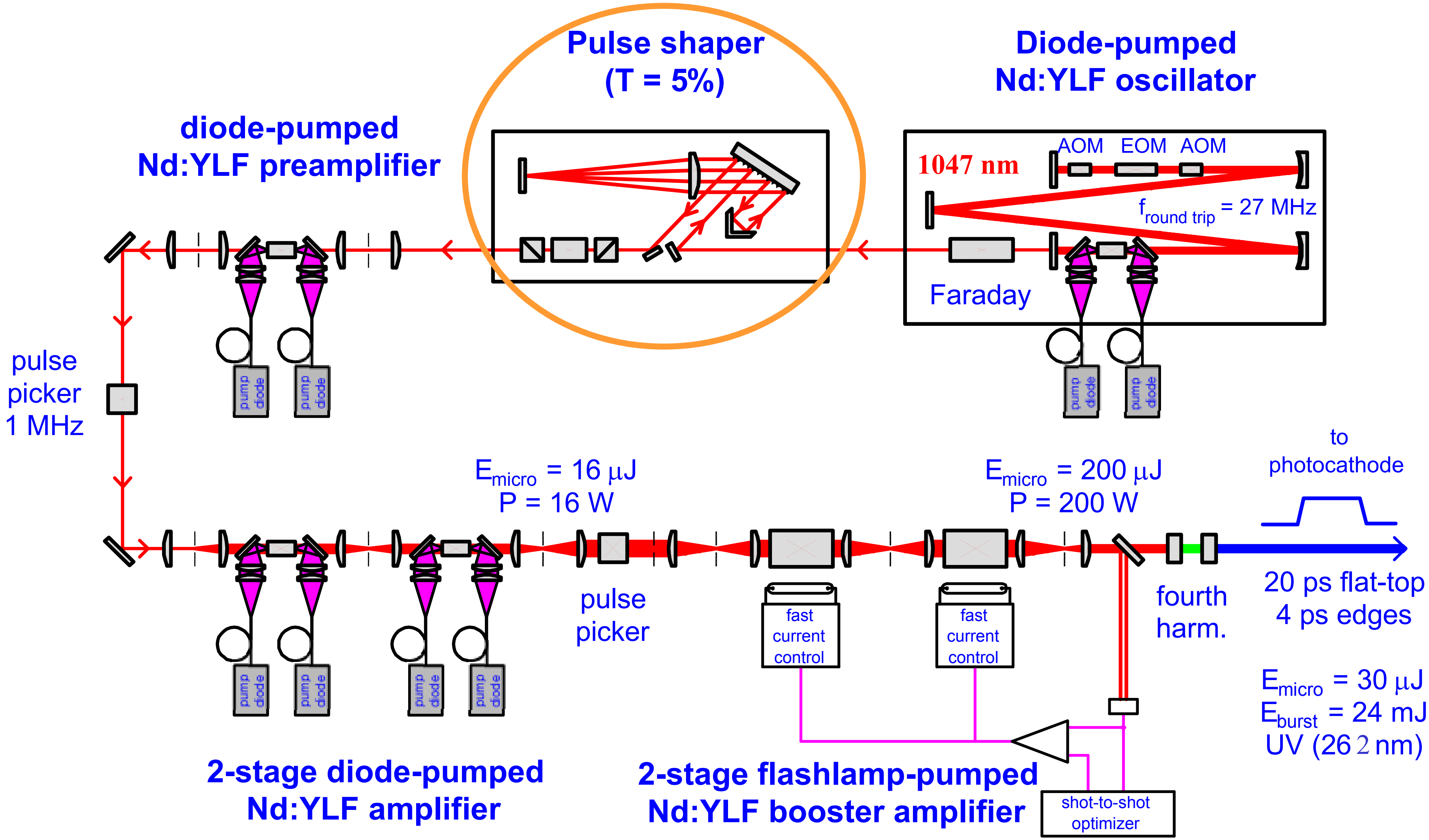
Experimental Results from PITZ@Zeuthen

Collaboration:

BESSY Berlin, DESY (HH + Z),
INFN Frascati, INFN Milano,
INR Troitsk, INRNE Sofia,
LAL Orsay, MBI Berlin,
TU Darmstadt, TU Eindhoven,
U Hamburg, YERPHI Yerevan

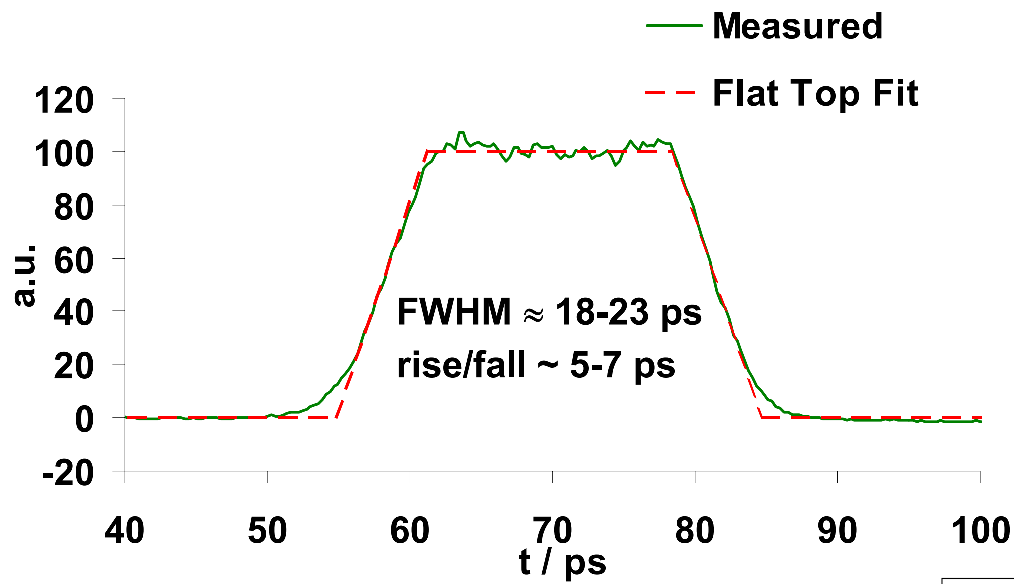


The Laser System at PITZ, ©MBI Berlin

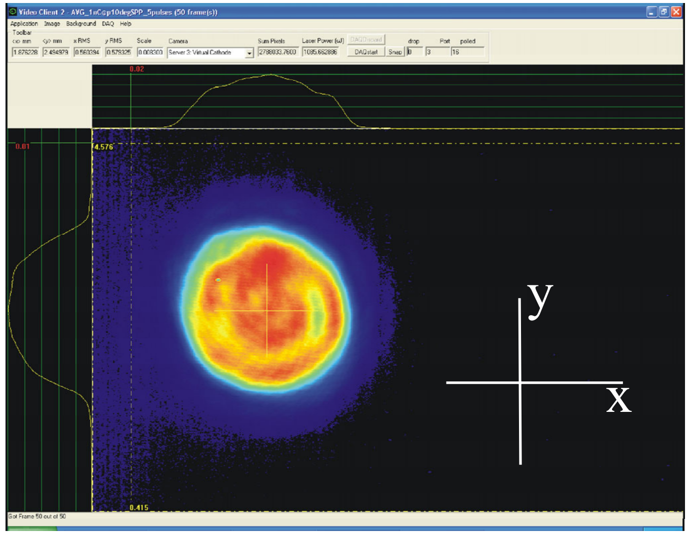


Longitudinal and Transverse Laser Profiles

longitudinal (measured at 524 nm)

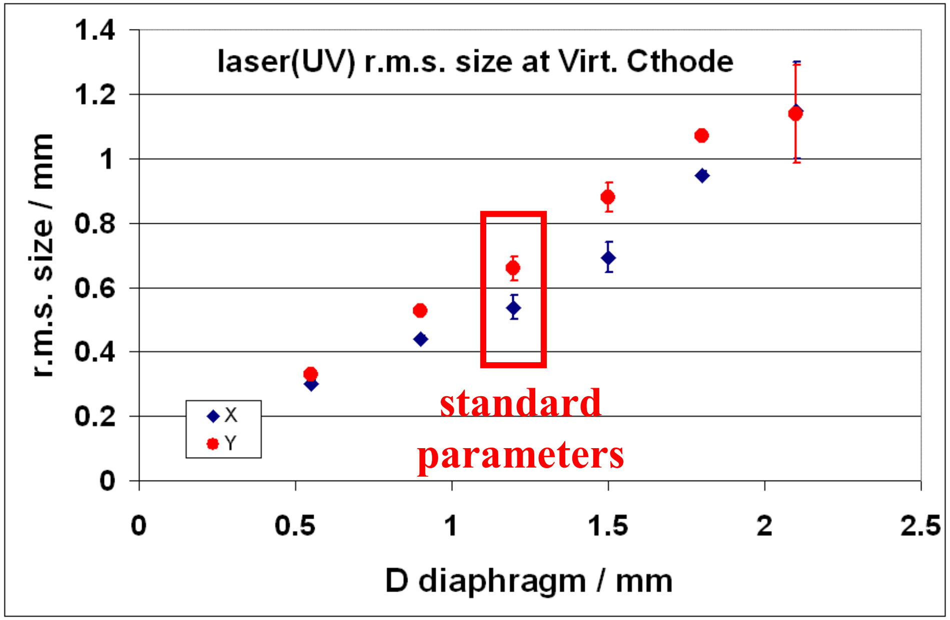


transverse (measured in UV at virtual cathode)



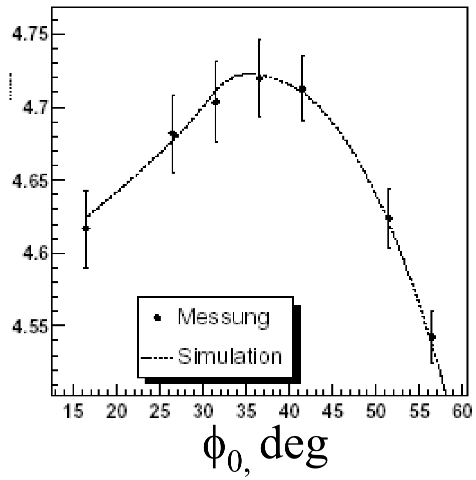
variable transverse size:

round diaphragms in the laser room (~ 20 m from the cathode) are imaged on the cathode

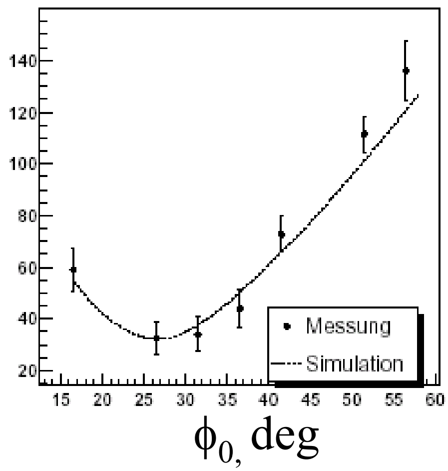


Longitudinal Momentum of the Electron Beam

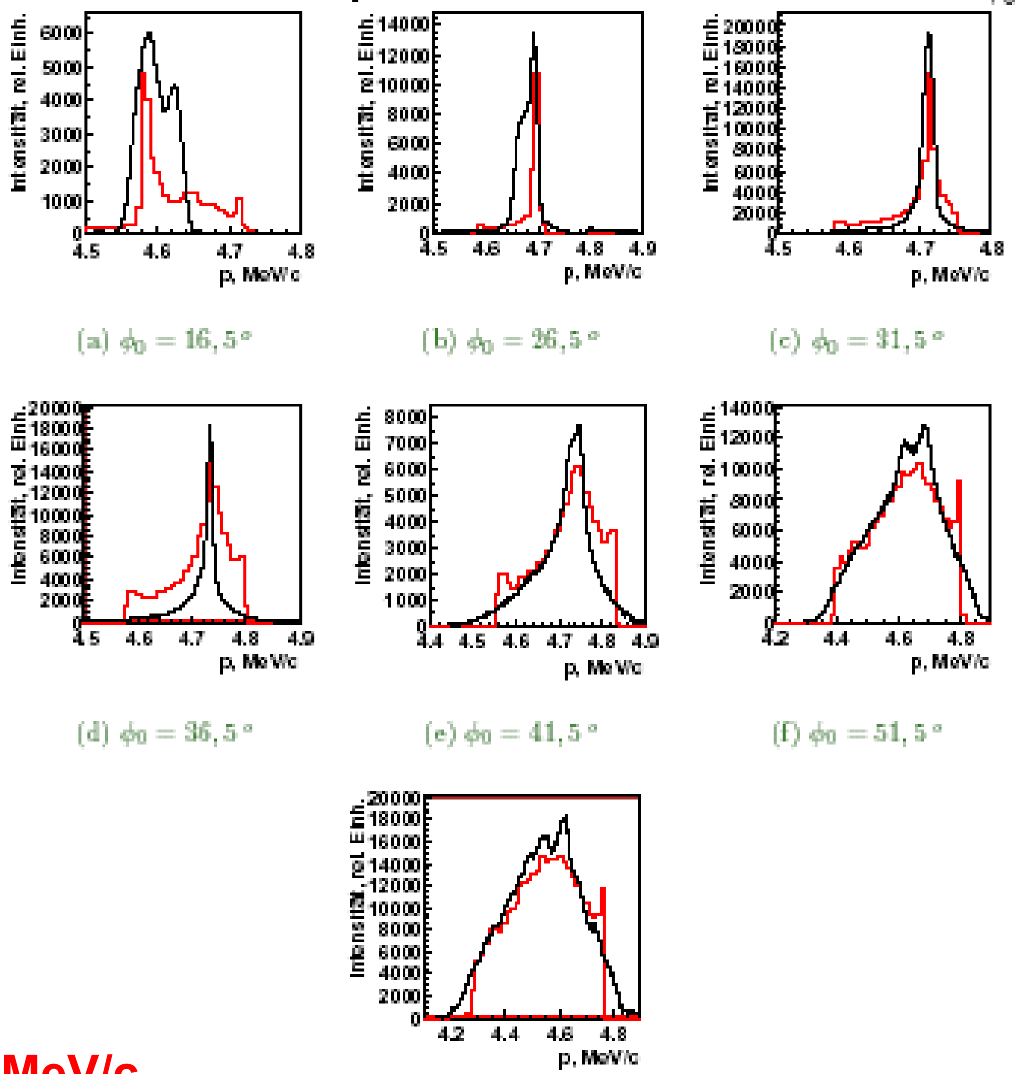
Mean momentum vs RF phase



RMS momentum spread vs RF phase



Measurement compared to simulation for different ϕ_0



(a) $\phi_0 = 16,5\,°$ (b) $\phi_0 = 26,5\,°$ (c) $\phi_0 = 31,5\,°$

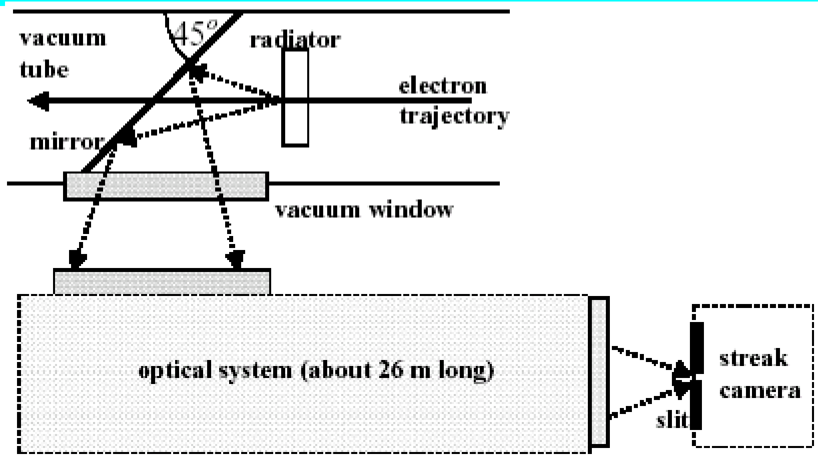
(d) $\phi_0 = 36,5\,°$ (e) $\phi_0 = 41,5\,°$ (f) $\phi_0 = 51,5\,°$

(g) $\phi_0 = 56,5\,°$

Maximum mean momentum 4.72 MeV/c

Minimum rms momentum spread 33 keV/c

Electron Beam Longitudinal Profile

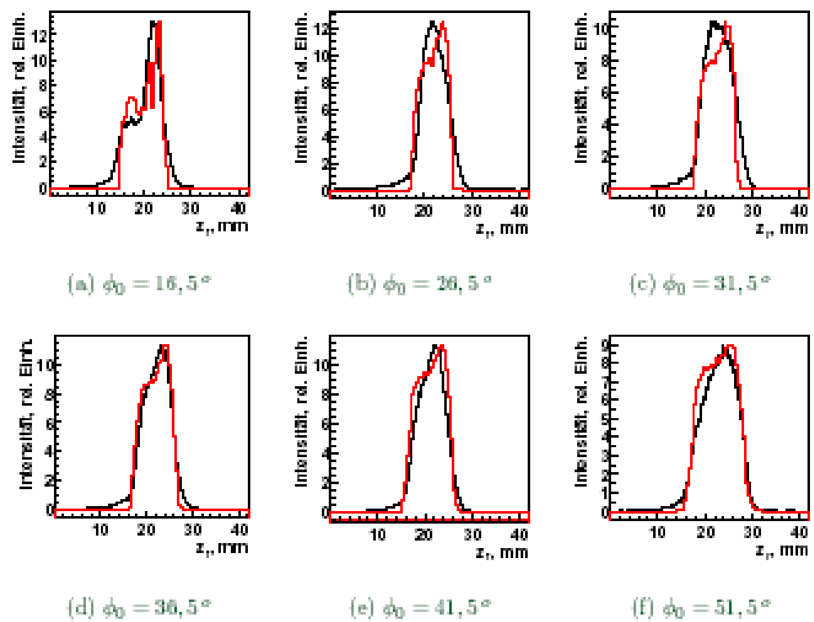


Cherenkov radiation

use of **aerogel**: SiO_2 ,

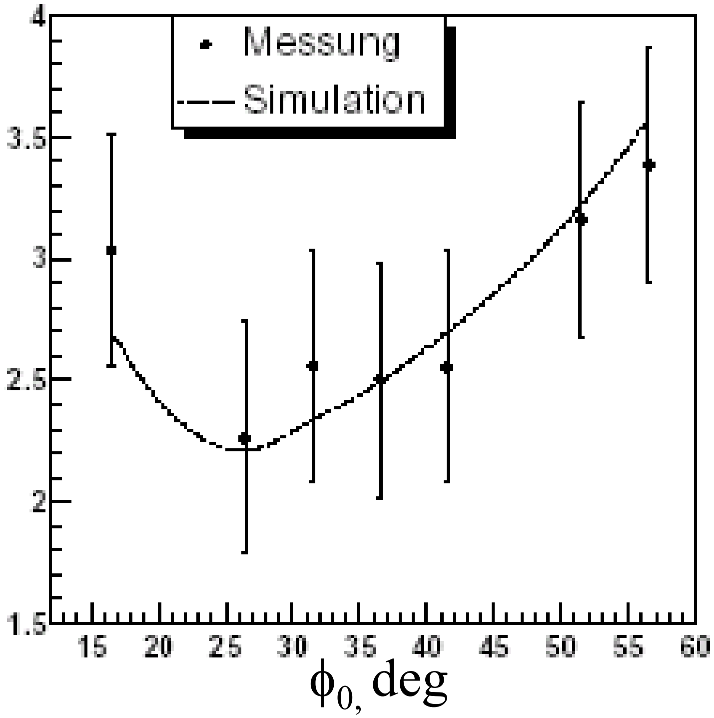
refractive index ≈ 1.03

Measurement compared to simulation for different ϕ_0



(a) $\phi_0 = 16,5°$ (b) $\phi_0 = 26,5°$ (c) $\phi_0 = 31,5°$ (d) $\phi_0 = 36,5°$ (e) $\phi_0 = 41,5°$ (f) $\phi_0 = 51,5°$

Bunch length (mm) in RMS 90 %:

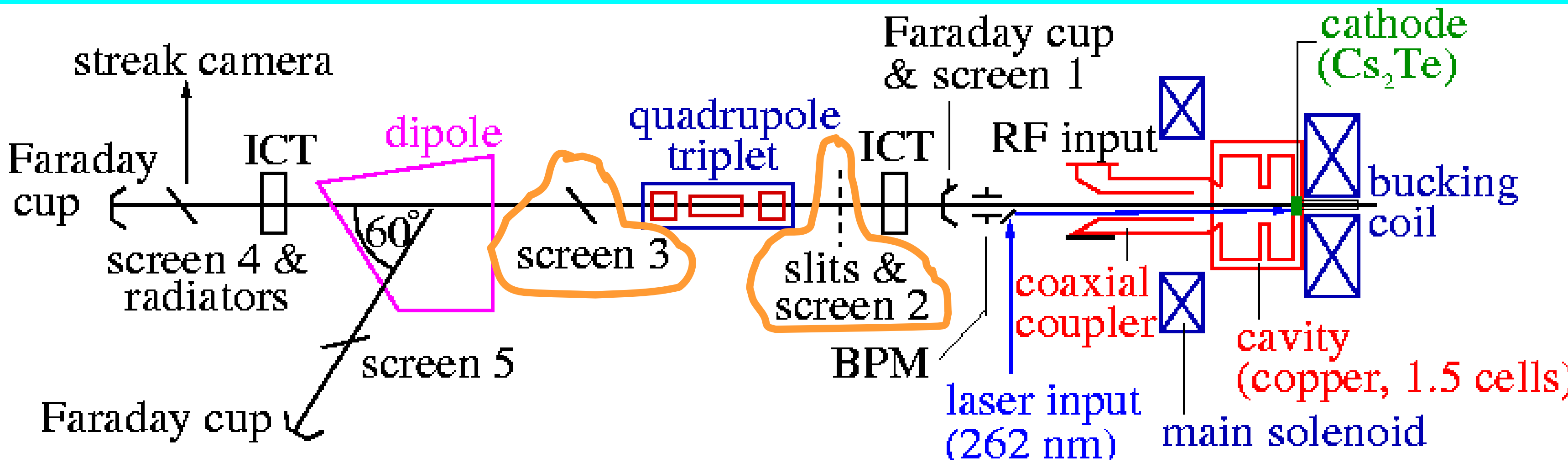


Minimum bunch length:

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

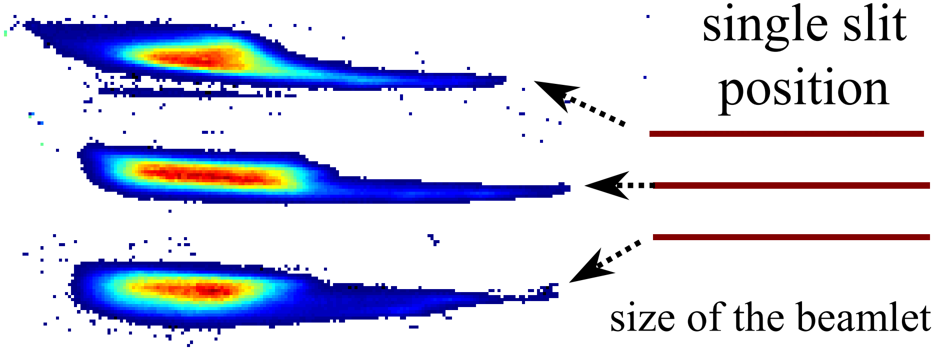
= (6.31 ± 0.14stat ± 1.24syst) mm

Transverse Beam Emittance Measurement

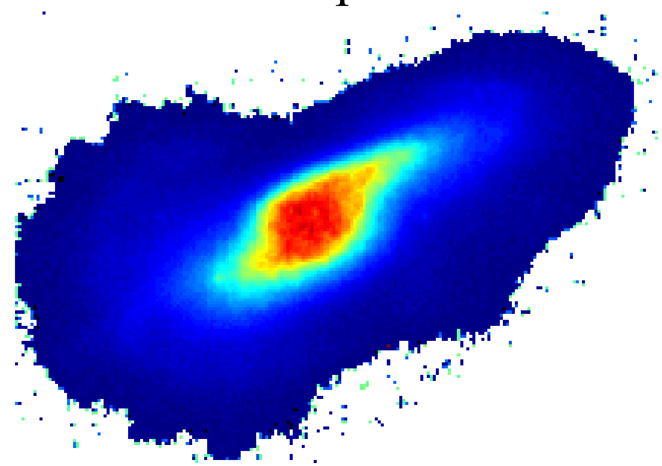


Single Slit Scan Technique

Beamlets at screen 3



Beam spot at screen 2



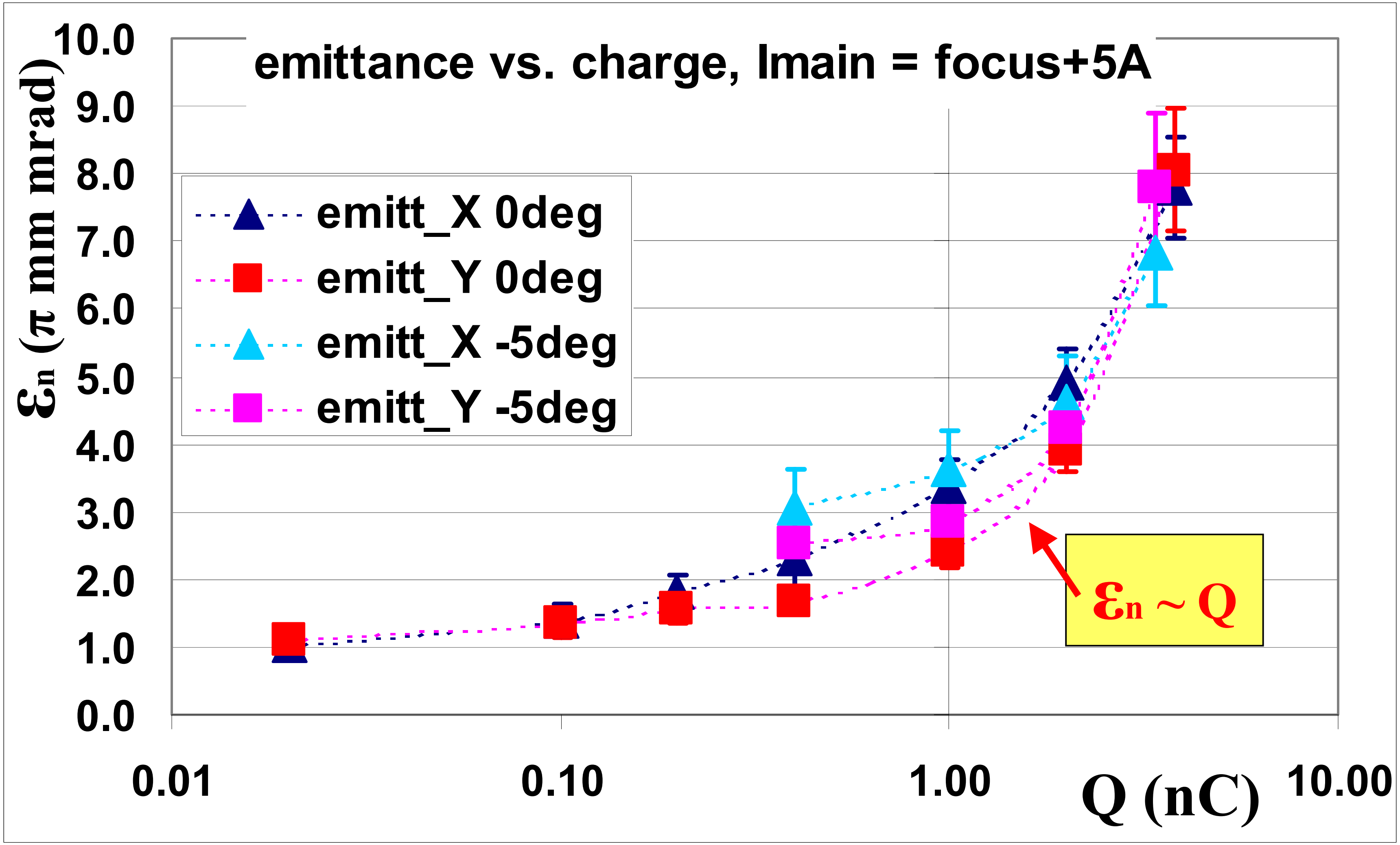
size of the beamlet is measured for three slit positions:

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

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

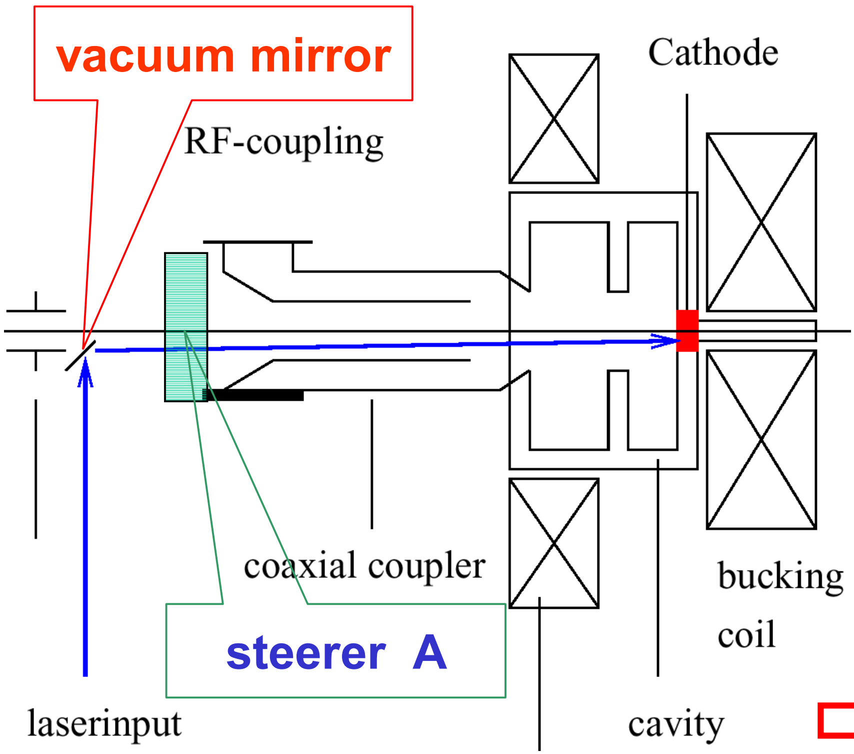
Transverse Emittance vs Bunch Charge

laser diaphragm diameter D = 1.0 mm (not final optimum)

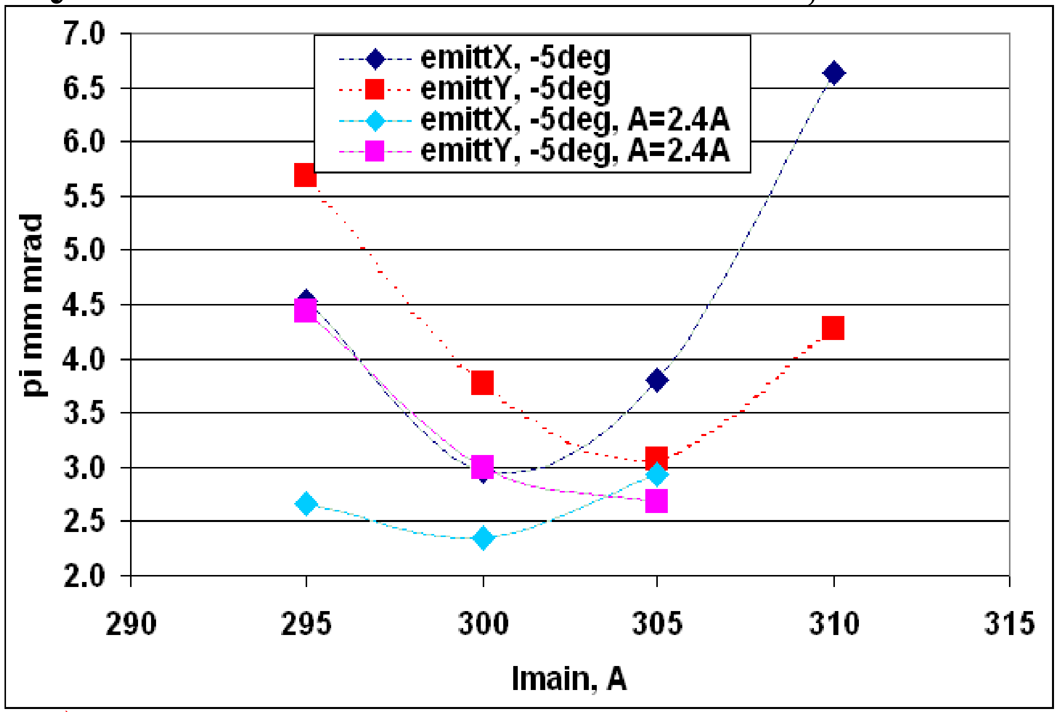


Steps to improve Beam Emittance

- **status in Sept. 2003: min. emittance ≈ 3 π mm mrad**
- **improvement: steer beam away from vacuum mirror**



1 nC, D = 1.2 mm



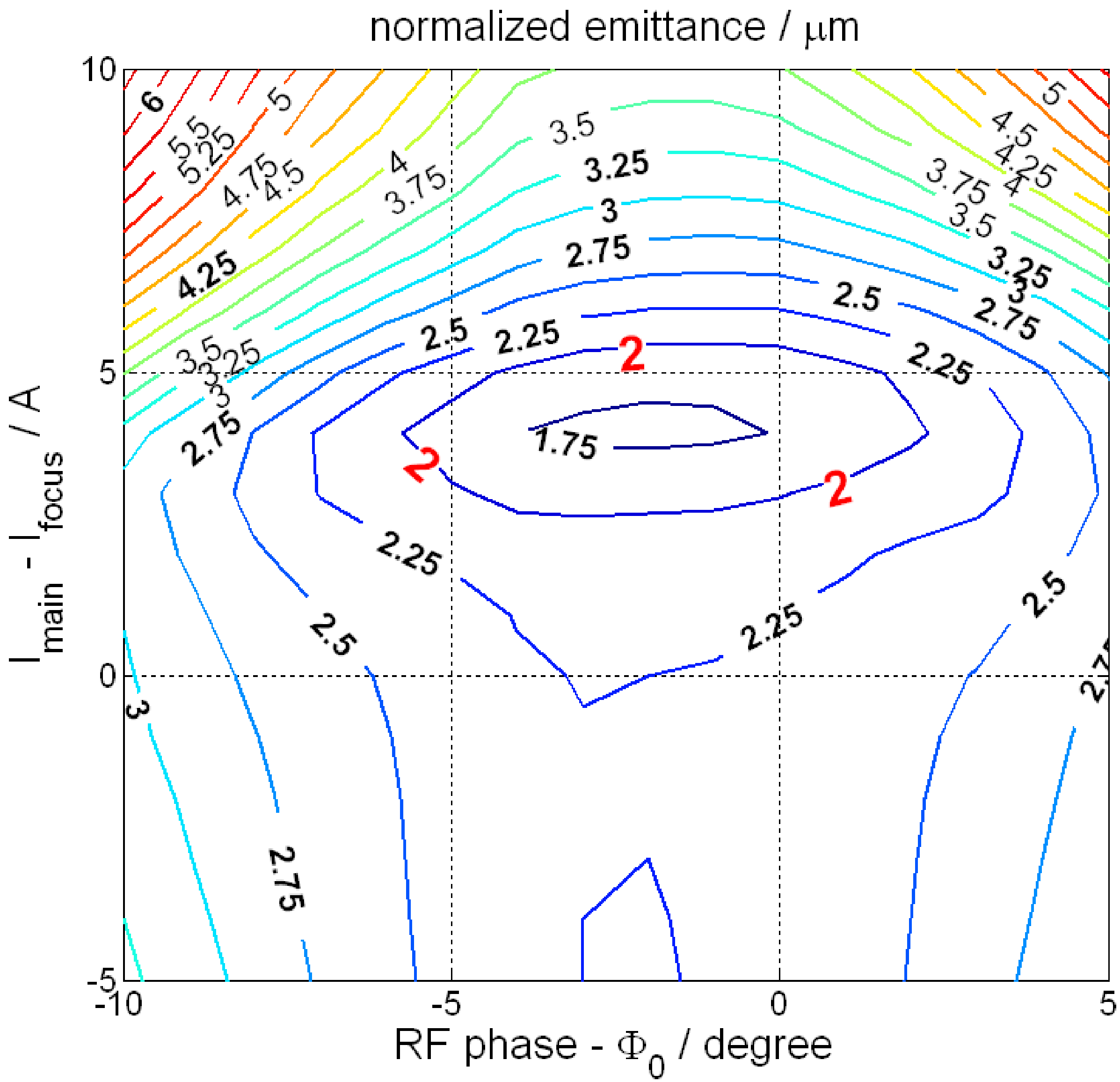
⇨ **improvement: > 0.5 π mm mrad**

- **systematic experimental optimization: long. laser profile, trans. laser profile, 2D scan Imain and RF phase, Ibuck for fine tuning**

ASTRA Simulation of Transverse Emittance

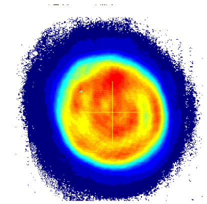
Parameters used for the simulation:

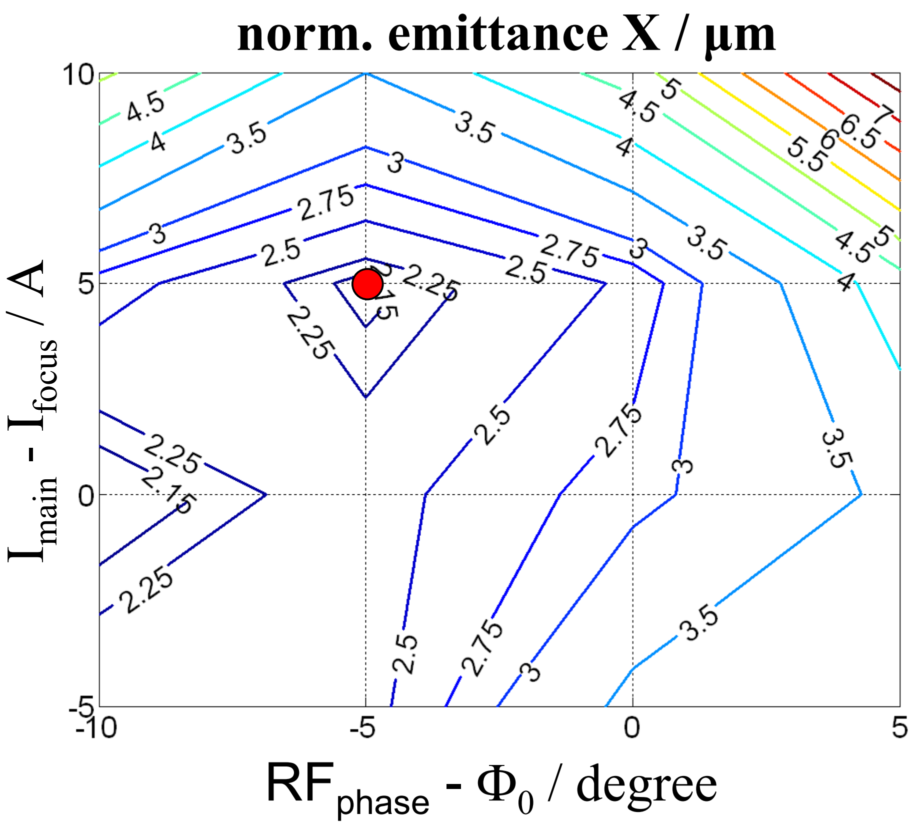
- **charge** = 1 nC
- **longitudinal laser profile**:
  - **flat top**
  - 20 ps FWHM
  - 5 ps rise/fall time
- **transverse laser profile**
  - **homogeneous**
  - $\sigma_{x,y}$ = 0.6 mm
- **max. gradient at the cathode**: 42 MV/m

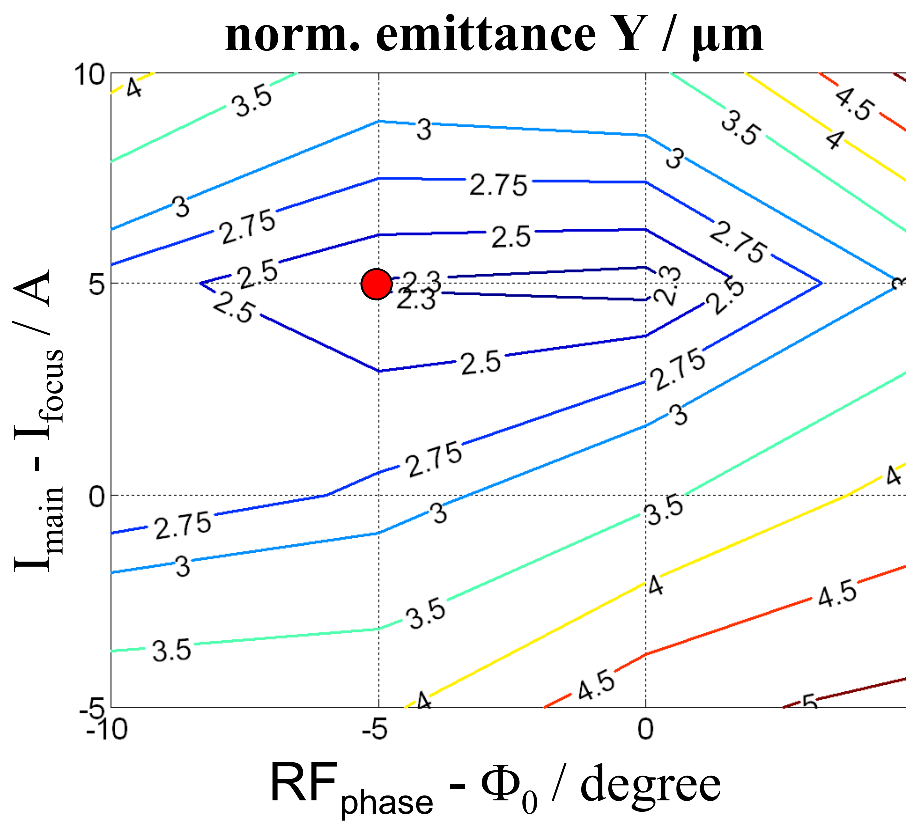


Transverse Emittance Measurements

Parameters: 1 nC, ~20 ps FWHM, ~7ps rise/fall time, diaphragm = 1.2 mm

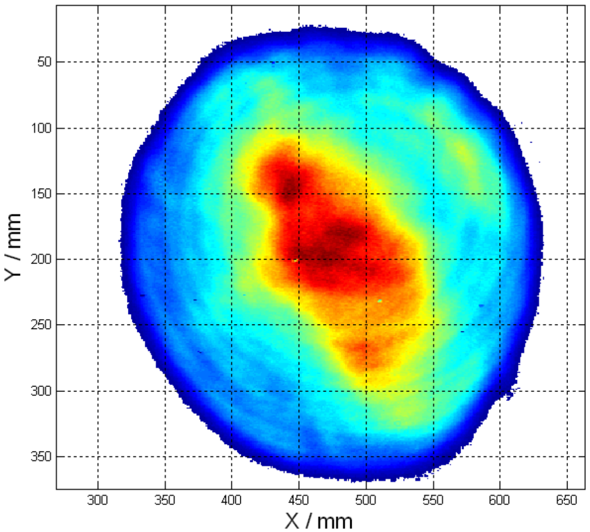






Fine Tuning of Laser Parameters

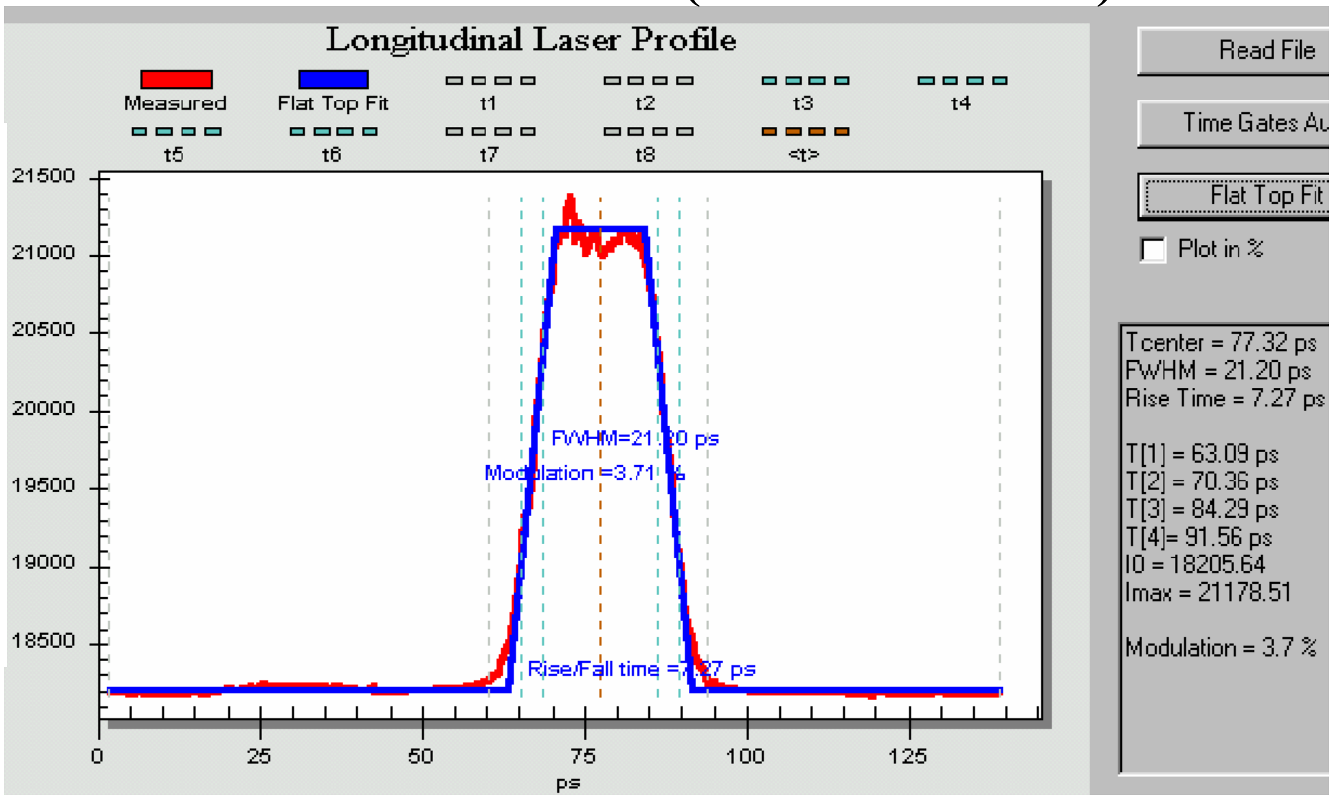
transverse profile
(D=1.2 mm)



$\sigma_x = 0.55 \pm 0.02$ mm

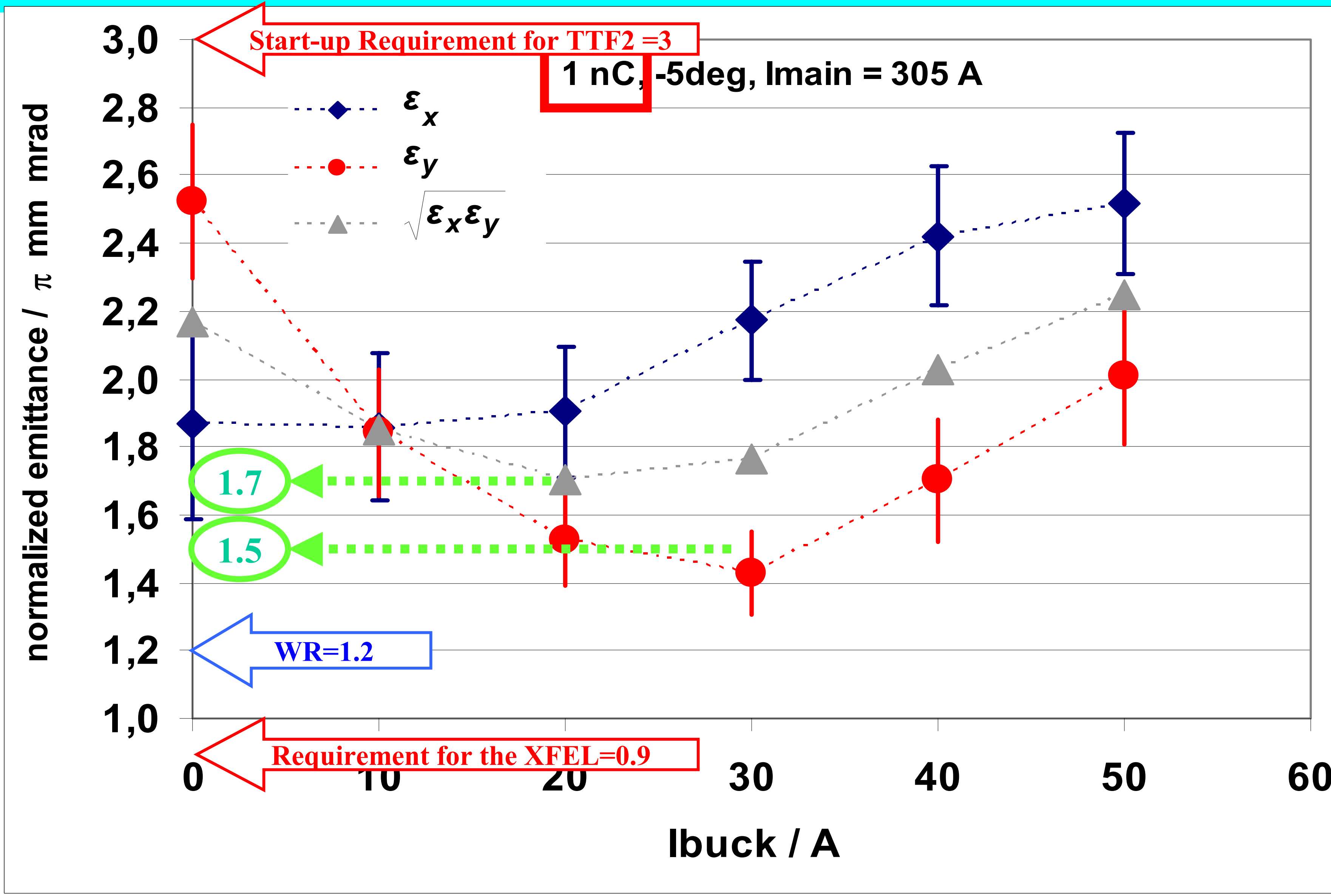
$\sigma_y = 0.61 \pm 0.02$ mm

(measured in UV)



FWHM ≈ 21 ps; rise/fall time ≈ 7 ps

Measured Transverse Emittance vs Bucking Solenoid



Start-up requirement of TTF2 is clearly fulfilled !

Summary PITZ1

- **electron beam was characterized in a wide range of machine parameters** *(e. g. Q, Φ_0, I_{main}, I_{buck}, laser parameters)*
- **optimum settings @ 1 nC:**

$$\sqrt{\varepsilon_x \varepsilon_y} = 1.7\ \pi\ \text{mm mrad}$$

$$\varepsilon_y = 1.5\ \pi\ \text{mm mrad}$$

have been reached with:

longitudinal laser shape:

'flat top', FWHM ≈ 21 ps, rise/fall time ≤ 7 ps

transverse laser profile:

'homogeneous', $\sigma_{x,y}$ ≈ 0.55 - 0.6 mm

solenoid current:

I_{main} ≈ 305 A, I_{buck} ≈ 20-25 A → **Bz** = 0 at cathode

RF parameters:

phase: $\Phi \approx \Phi_0 - 5°$, gradient at cathode: ~ 42 MV/m

- **cavity is now installed at TTF2**

How to reach the beam quality required for XFEL

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

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

    ⇒ **ε_n ~ 1.5 π mm mrad @ 1 nC** (ongoing in 2004)

  - improved longitudinal laser profile (2 ps rise/fall time):

    ⇒ **ε_n ~ 1.2 π mm mrad @ 1 nC** (realisation in ~2004-2006)

- in addition, with **60 MV/m** at the cathode:

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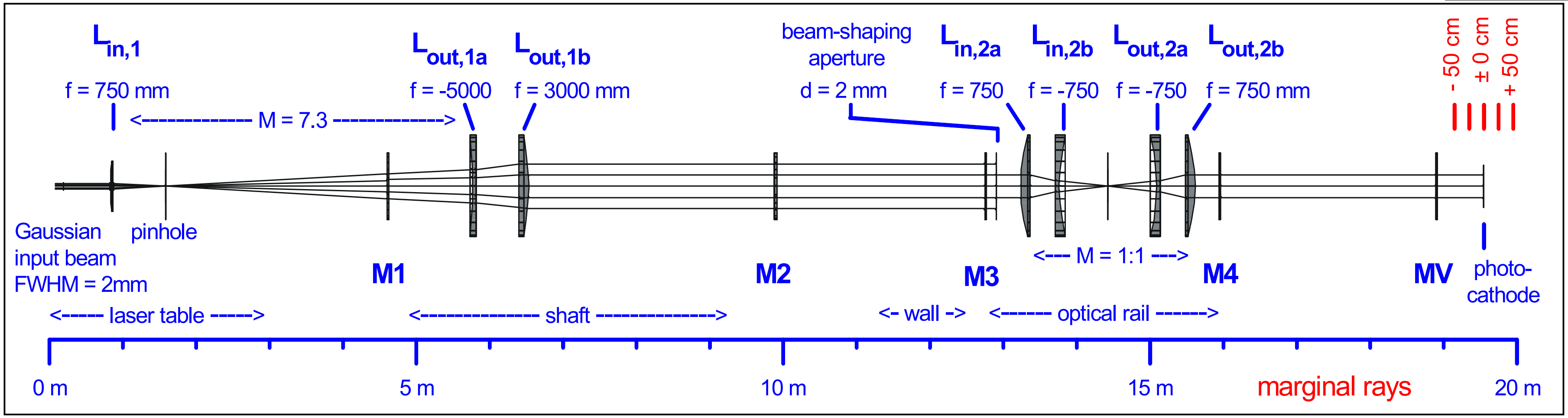
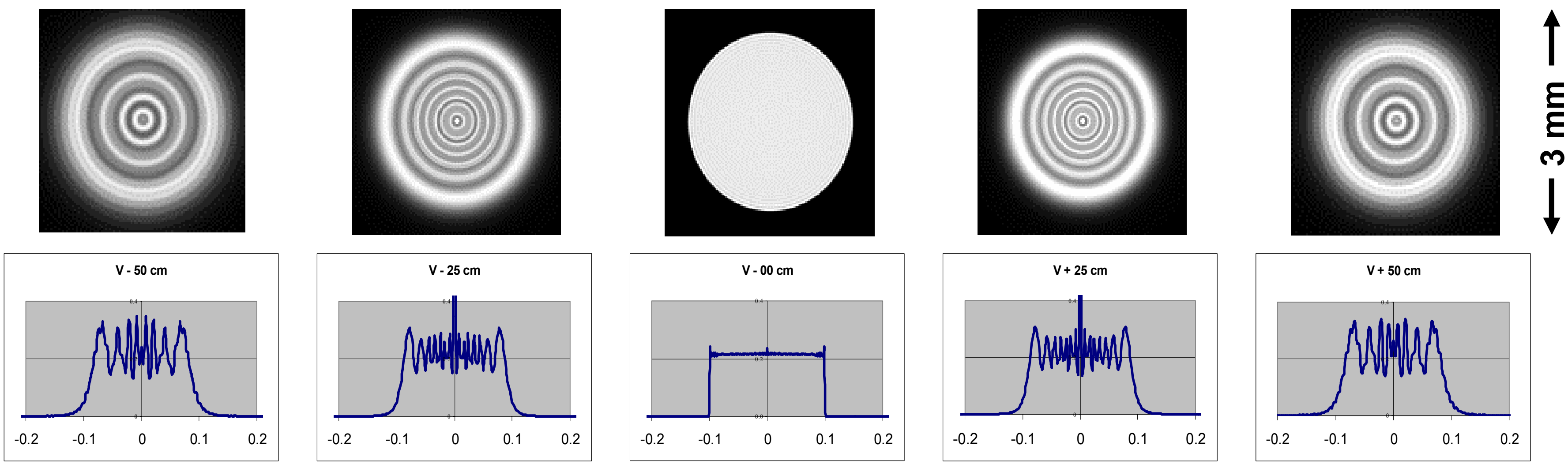
Proposed Setup for Laser Beam Line to Cathode

© I. Will (MBI), status: Draft



Z_0 - 50 cm | Z_0 - 25 cm | Z_0 | Z_0 + 25 cm | Z_0 + 50 cm



How to reach the beam quality required for XFEL

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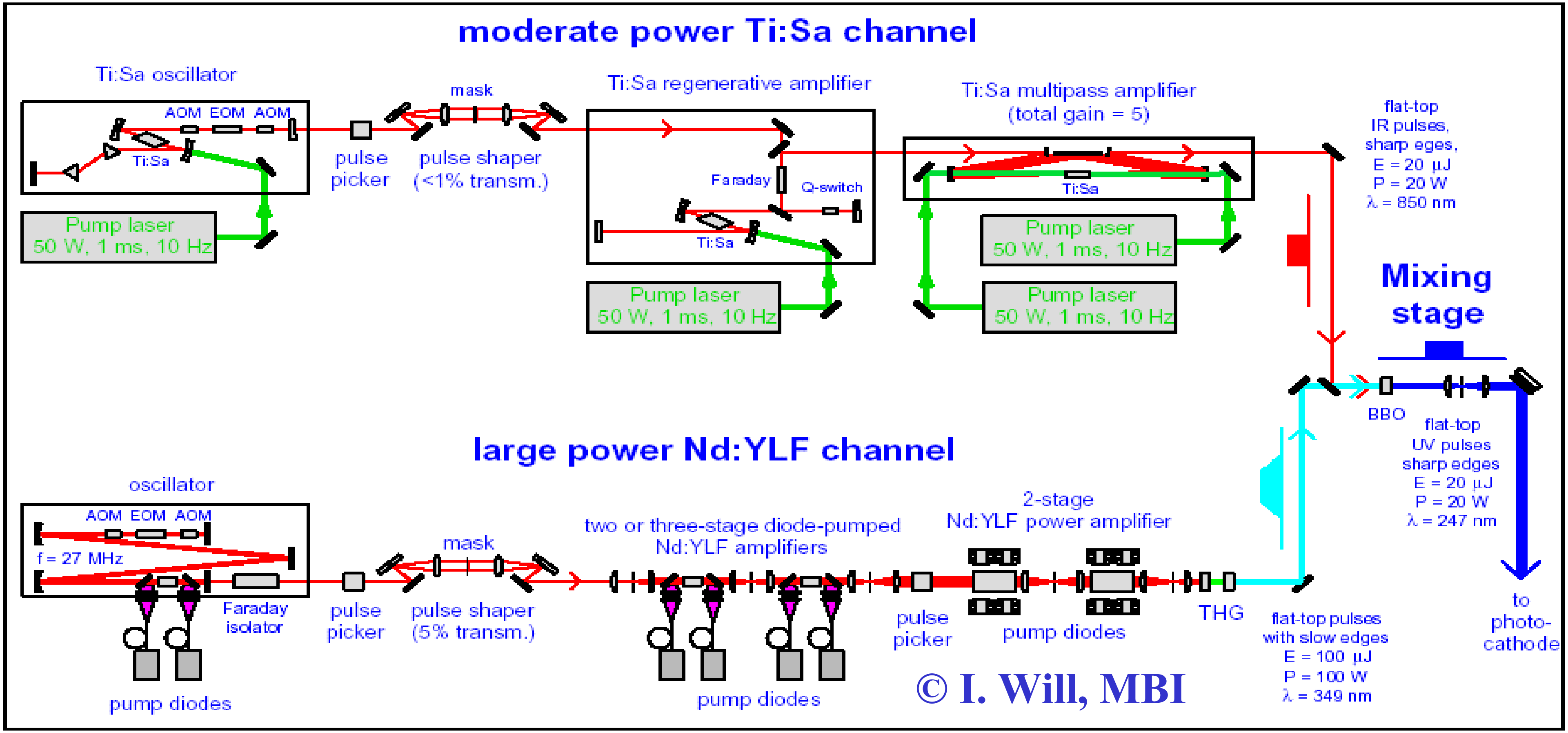
Photo Cathode Laser Development for PITZ 2

Goals: - stable and reliable laser system for **long pulse trains**

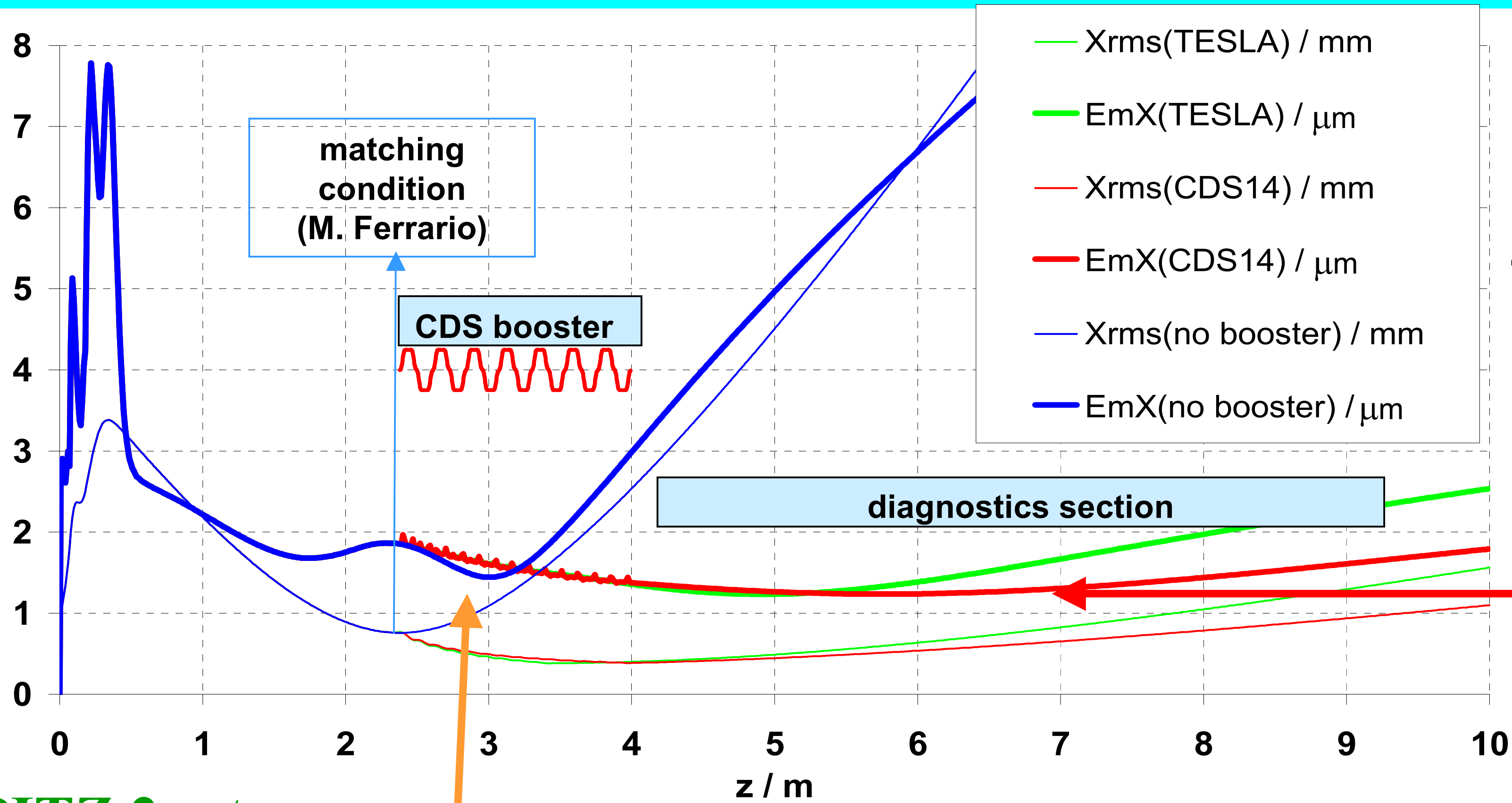
- micropulses temporal profile: **20 ps FWHM**, **rise and fall time ≤ 2 ps**
- **homogenous** transverse intensity profile
- laser parameters widely **variable**

Strategy:

- further improve the Nd:YLF laser system
- two-channel mixing scheme



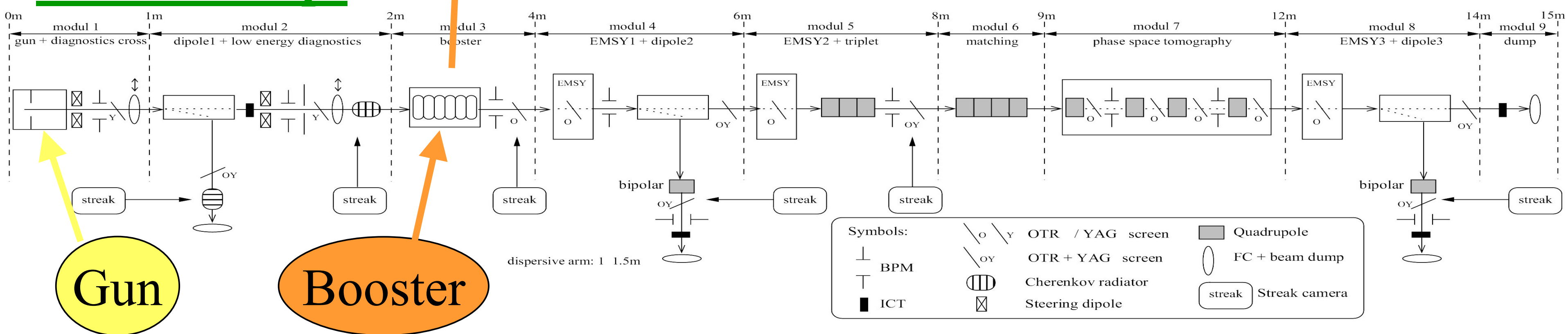
ASTRA Simulation of PITZ 2 (20ps FWHM, 2ps rise/fall time)



used gun gradient: 40 MV/m

ε_n = 1.2 µm

PITZ 2 setup:



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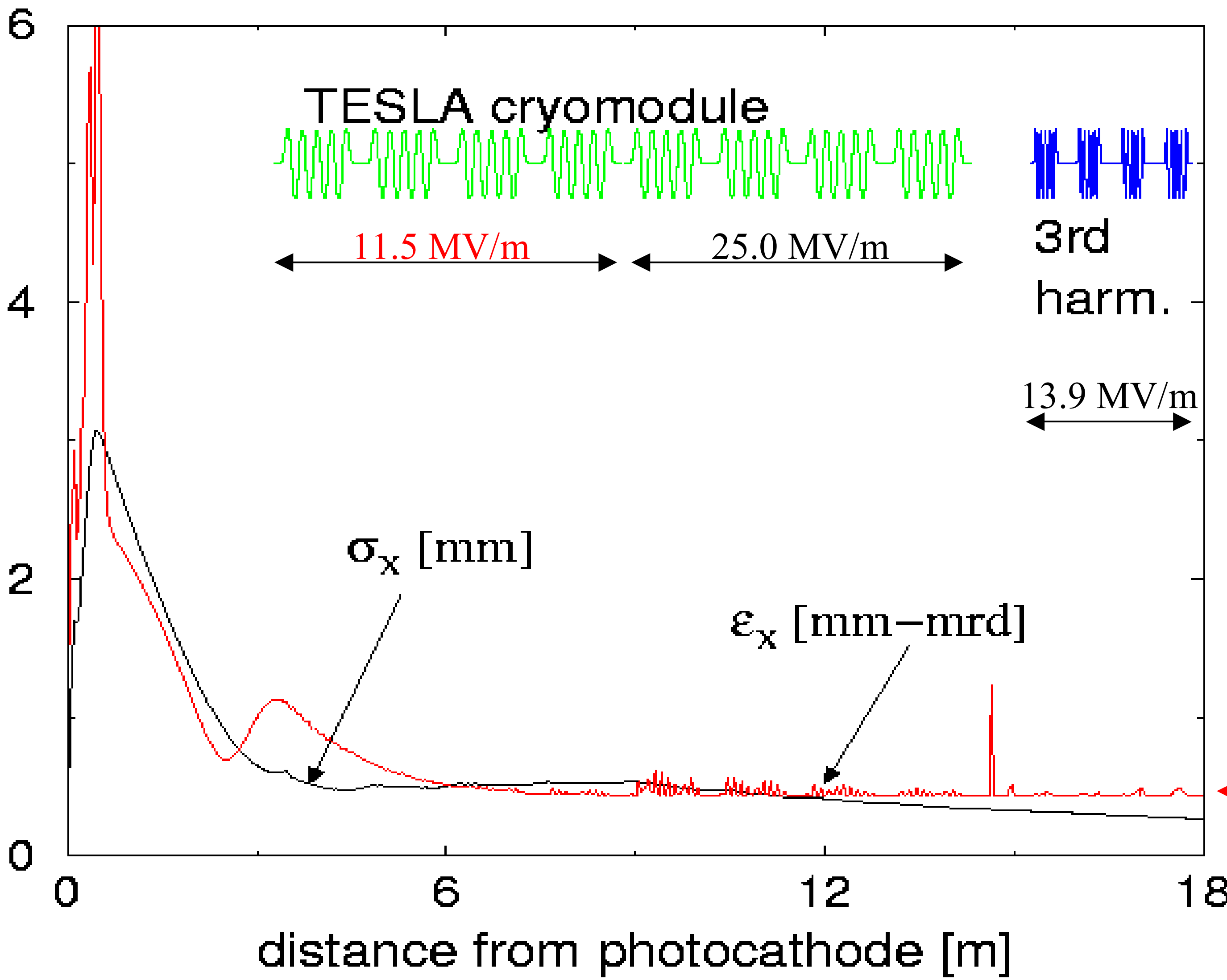
Transverse Beam Parameters for the XFEL Injector



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)