Transverse emittance measurements at PITZ

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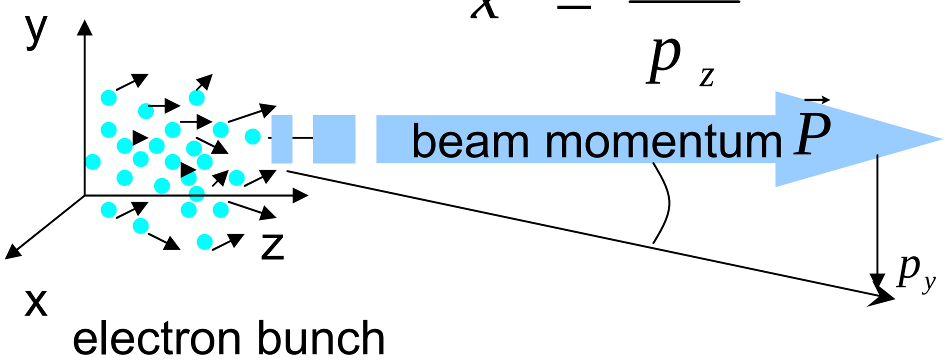
Joint DESY and University of Hamburg
Accelerator Physics Seminar

Outline

- Emittance of the electron beam
- Motivation
  - SASE FEL
  - FLASH, XFEL and PITZ
- PITZ in details
  - hardware setup, operation parameters
- Emittance Measurement SYstem (EMSY)
  - optimization and error analysis
- Emittance measurement results at PITZ
  - optimized parameters
  - two different gun cavities
- Discussion

Emittance

introduction



$$x' = \frac{p_x}{p_z}$$

$$(x, y, z, x', y', p_z)$$

$$f(x, y, z, x', y', p_z)$$

emittance is related to volume/area occupied by the electrons, the smaller - the better

→ central moments $\langle \cdots \rangle$
→ 2D projections *f(x, x')*

→ covariance matrix $\Sigma_x = \begin{pmatrix} \langle x^2 \rangle & \langle xx' \rangle \\ \langle xx' \rangle & \langle x'^2 \rangle \end{pmatrix}$

→ matrix representation $\Sigma_x' = R \cdot \Sigma_x \cdot R^T;$

→ transfer matrices $R = D_1 \cdot Q_1 \cdot D_2 \cdot Q_2 \cdot \ldots \cdot D_n \cdot Q_n \ldots$

Emittance

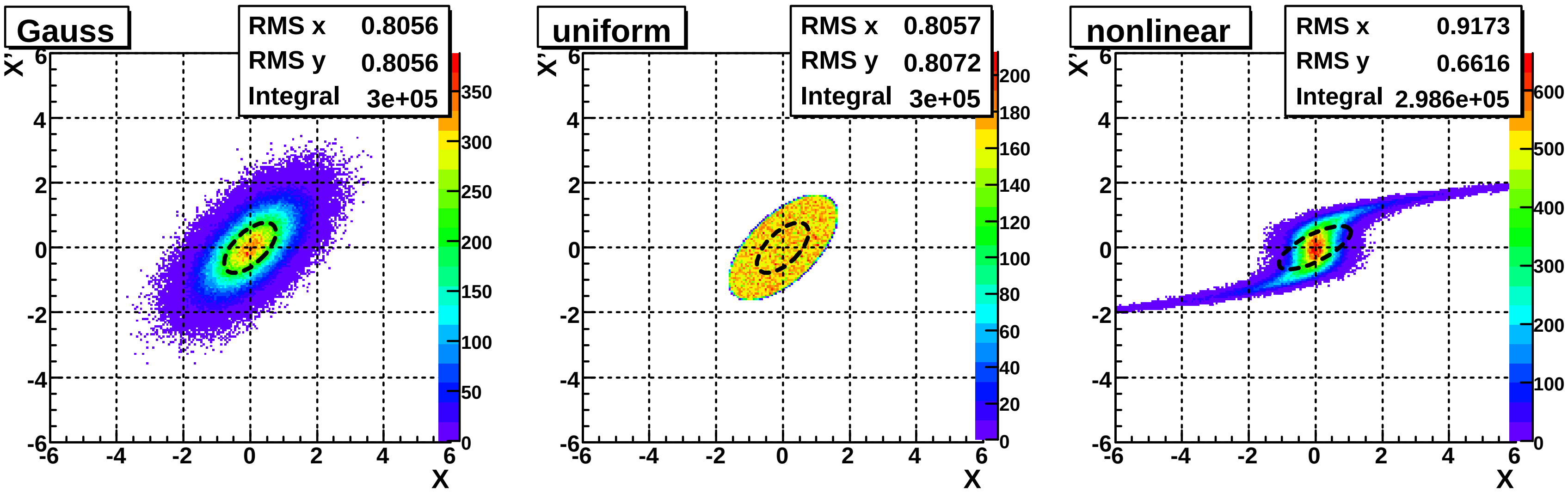
definition

$$\Sigma_x = \begin{pmatrix} \langle x^2 \rangle & \langle xx' \rangle \\ \langle xx' \rangle & \langle x'^2 \rangle \end{pmatrix}$$ ← covariance matrix

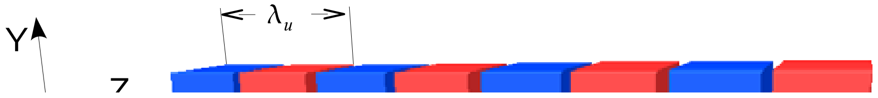
$$\det|\Sigma_x| = \varepsilon_{rms}^2$$

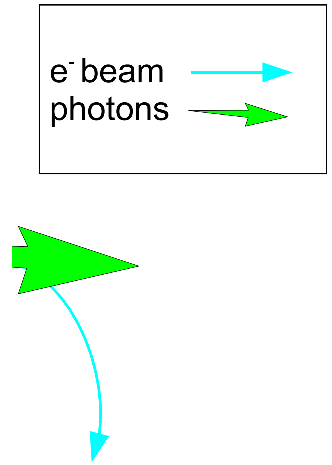
$$\det|\Sigma_x| \cdot \beta\gamma = \varepsilon_{rms,n}^2$$

RMS normalized emittance: $$\varepsilon_{x,rms} = \beta\gamma \cdot \sqrt{\langle x^2 \rangle \cdot \langle x'^2 \rangle - \langle xx' \rangle^2}$$



European XFEL design parameters



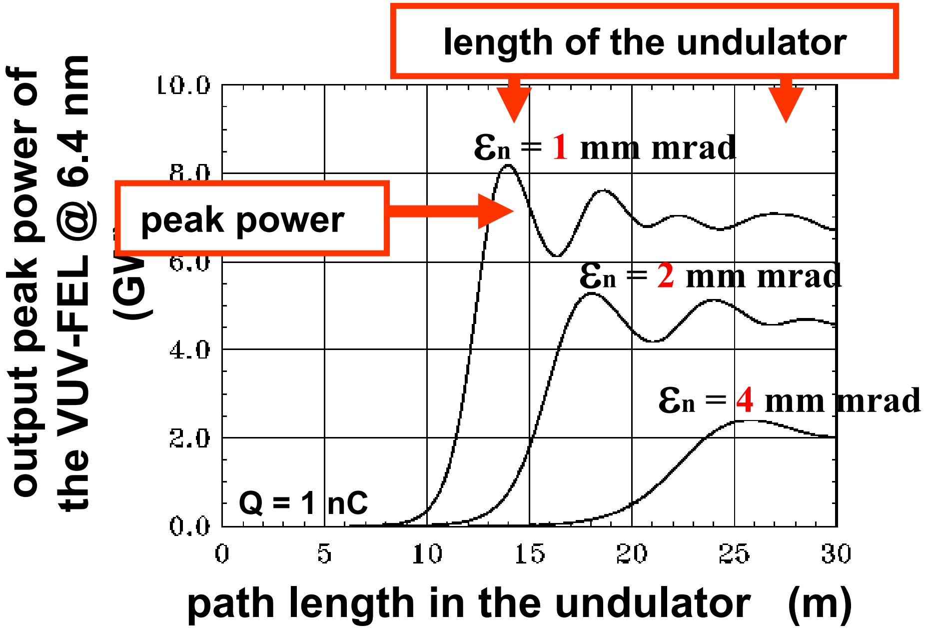


- Electron beam
  - high peak curre — ~5 kA
  - short bunch — 20 μm
  - small emittance — 1.4 mm.mrad
- Undulator
  - strong field — 1.5 T
  - precise alignme — 32μm/260m
  - very long — 100^s m
- SASE FEL
  - short waveleng — 0.1 nm
  - high brilliance — 10^{33} photons/s/mm^2/mrad^2/0.1%
  - ultra short puls — < 100 fs

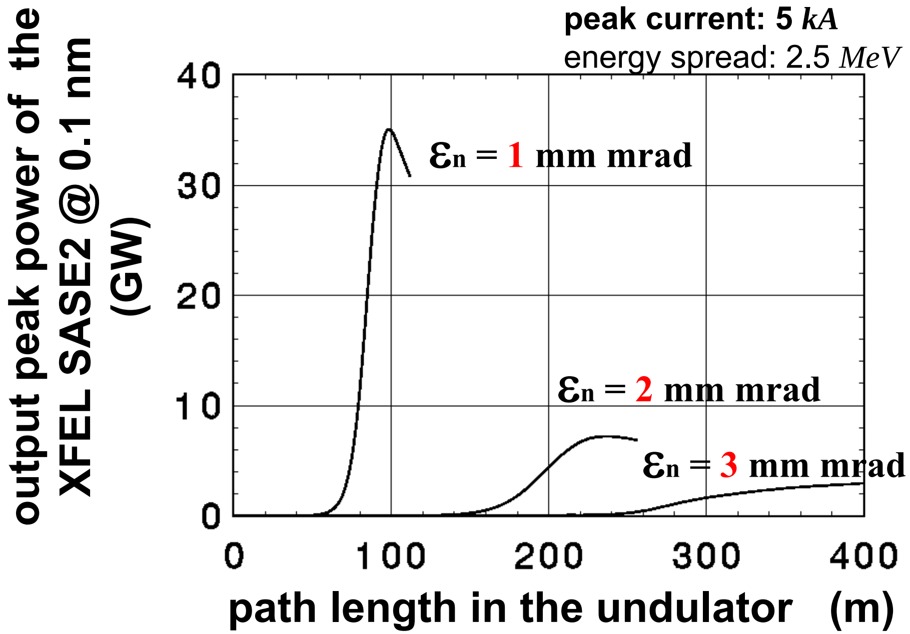
Emittance

the smaller-the better

VUV-FEL (FLASH)



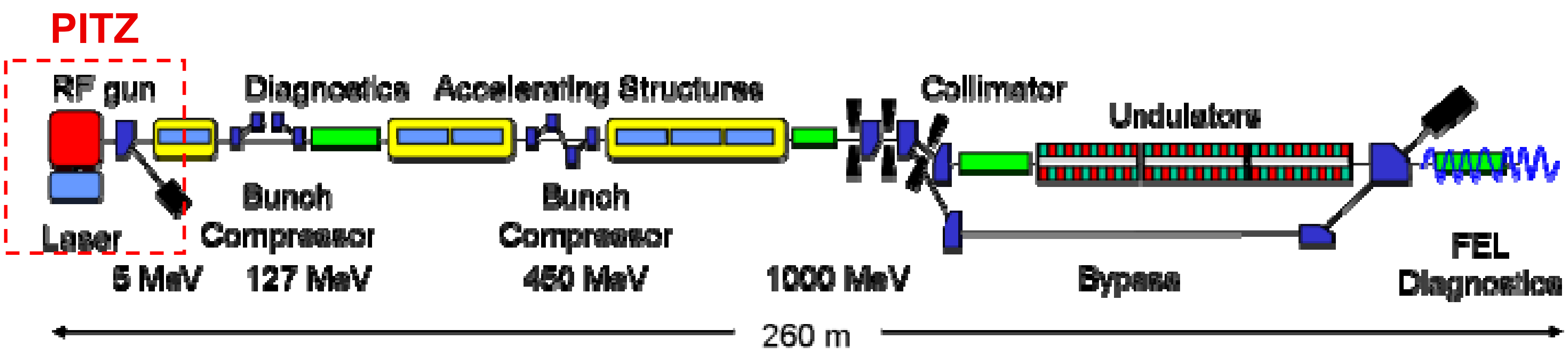
XFEL



- **XFEL goal: 0.9 *mm mrad*@injector ⇒ 1.4 *mm mrad*@undulator**
- **if even smaller emittance ⇒ new horizons:**
  shorter wavelength, higher repetition rate

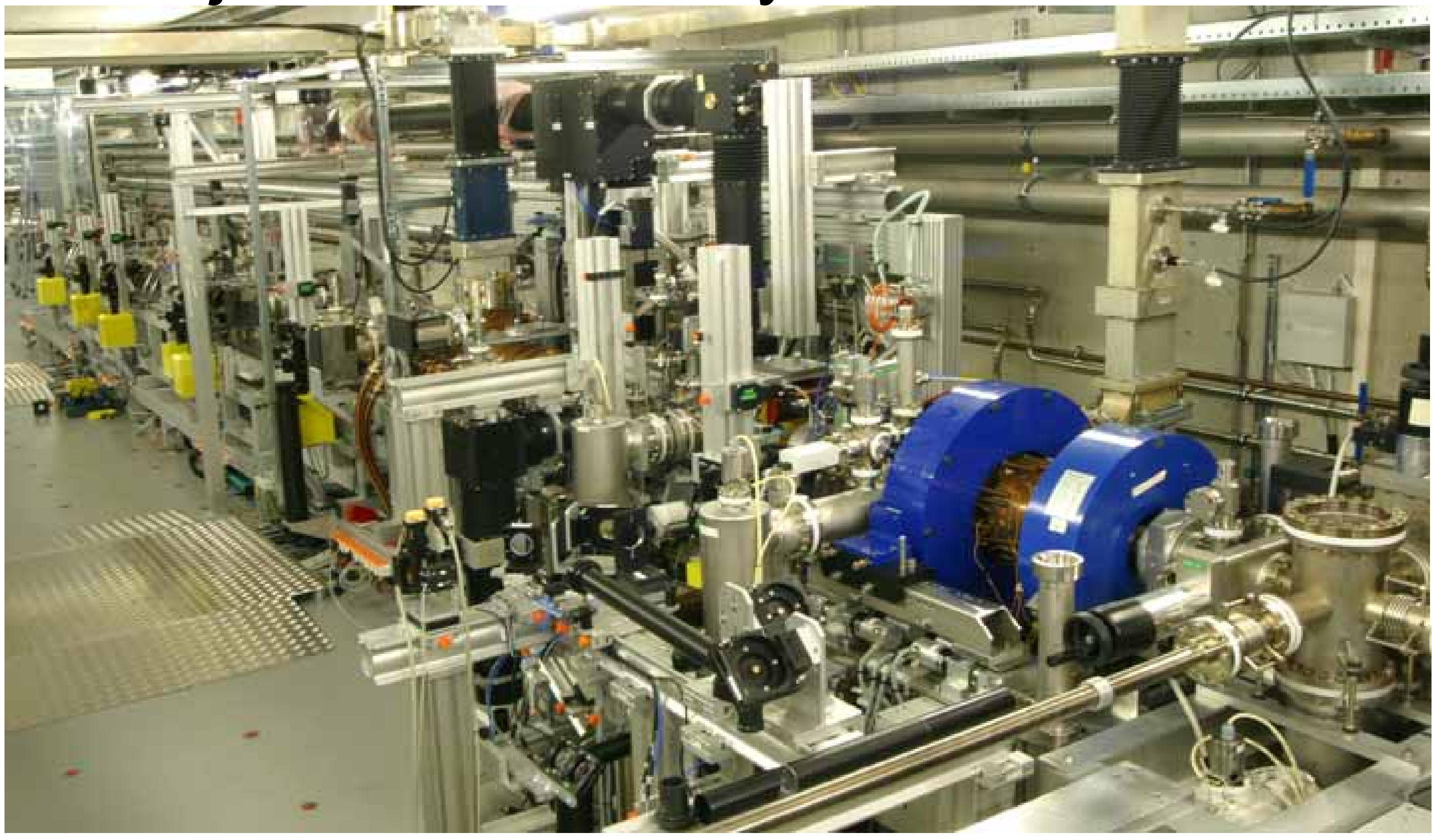
FLASH layout

- e^- source
- pre acceleration
- bunch compression
- further acceleration compression
- final acceleration
- collimation and undulation



PITZ

- Photo Injector Test-facility at DESY in Zeuthen



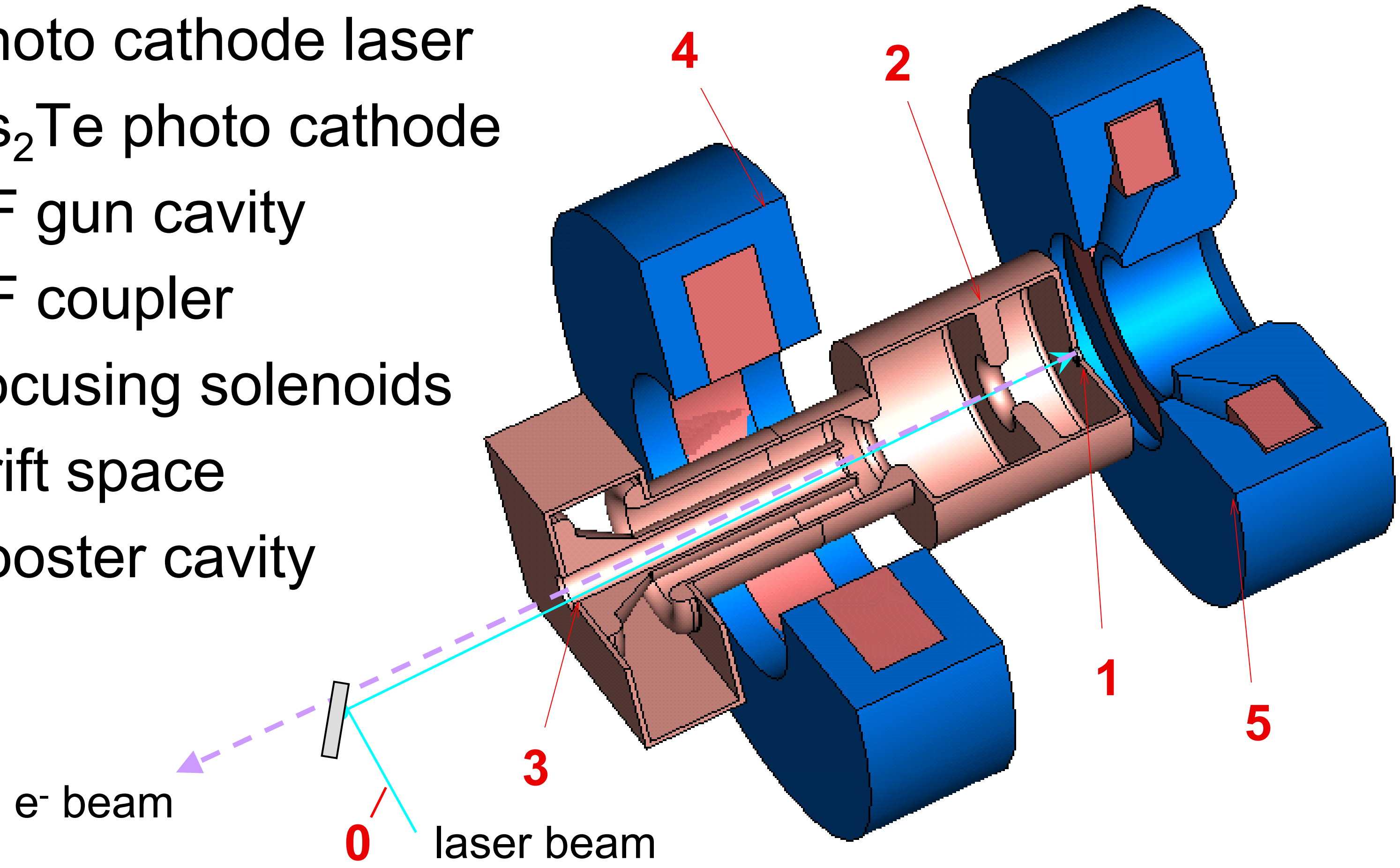
RF photo-injector

0. Photo cathode laser
1. Cs_2Te photo cathode
2. RF gun cavity
3. RF coupler

4, 5. Focusing solenoids

Drift space

Booster cavity



Extraction from Cs_2Te cathode

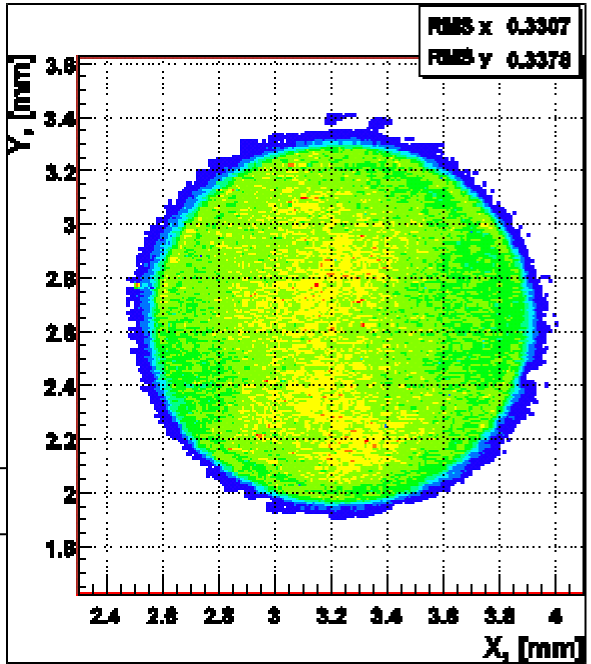
- photo effect - quantum efficiency of Cs_2Te cathode (Q.E.) etc.
- “Schottky effect” – lowering the potential barrier to the vacuum
- thermal emittance – remnant kinetic energy after the electron extraction
- mirror and space charge

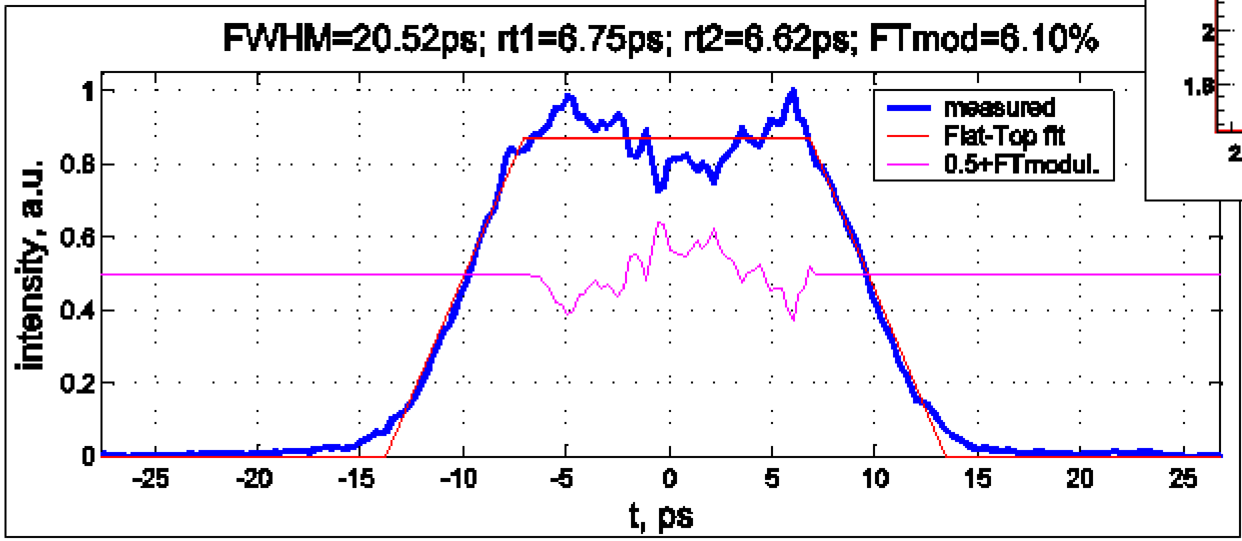
Extraction

Photo-cathode laser

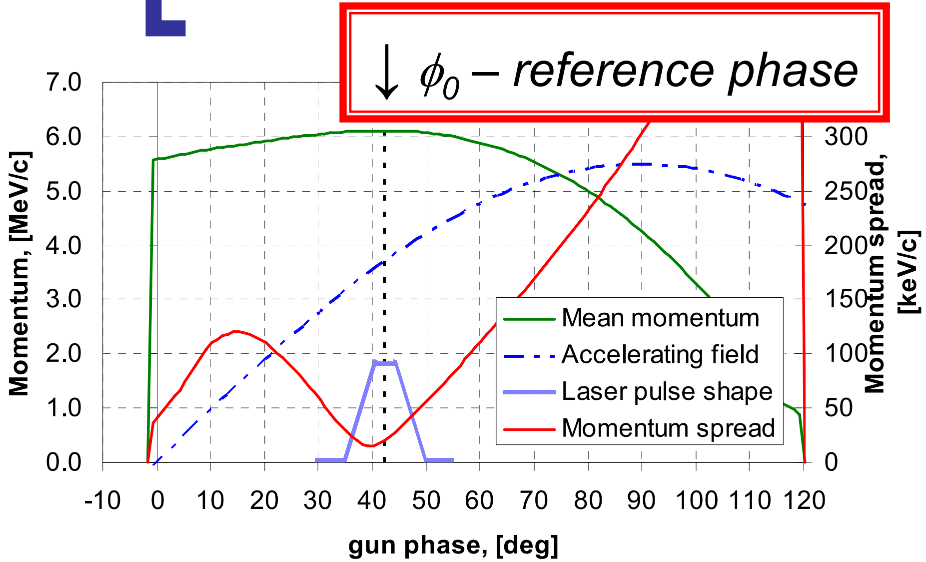
PTO, pulse-shaper, Nd:YLF pumped amplifier, frequency converter

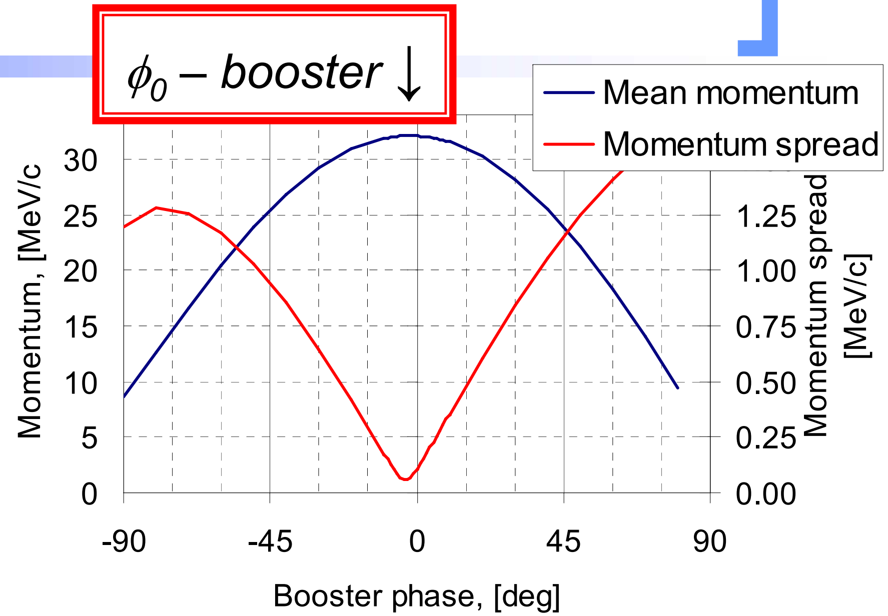
- λ=262 *nm*
- rise/fall time = 6 ps (2 ps upgrade)
- FWHM = 20 *ps*
- σ_{xy} – tunable 0.1 to 3 *mm* diameter



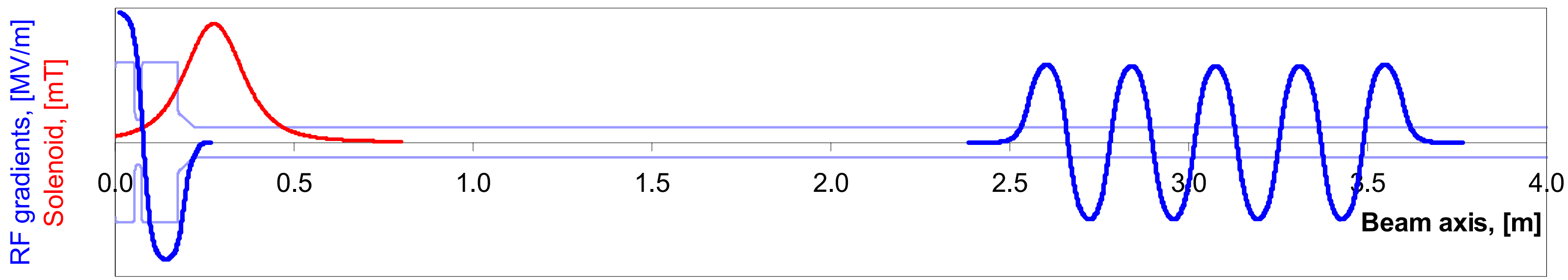


Acceleration



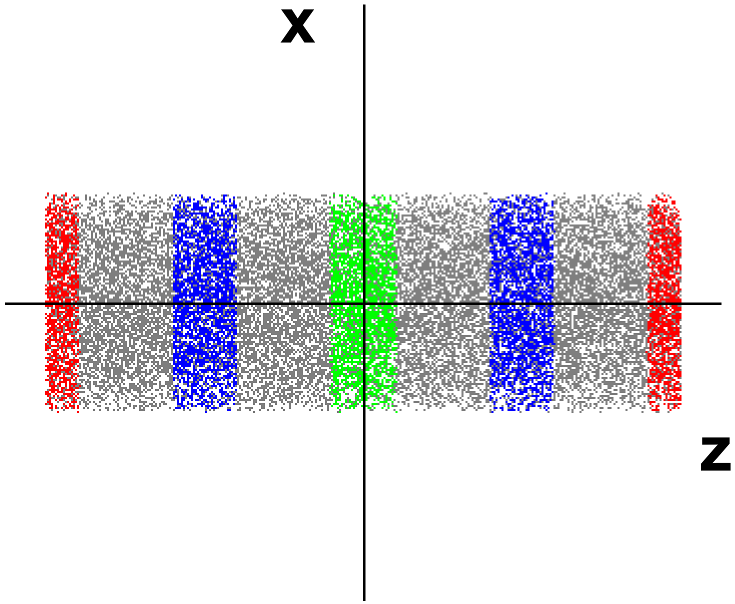


$$E_{acc} = E(z) \cdot \sin(\omega t + \phi)$$

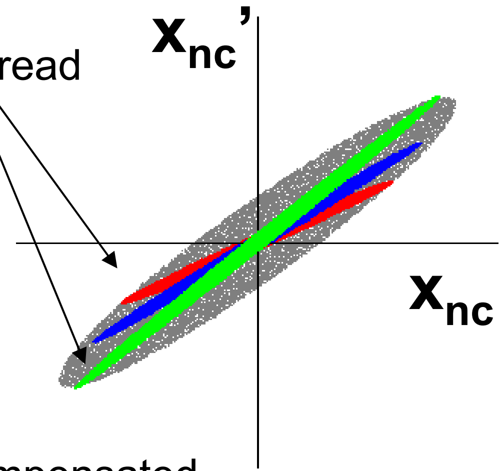


Emittance compensation
solenoid, linear space charge

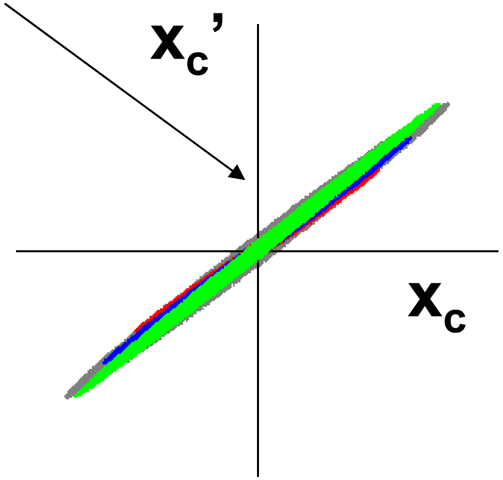
Longitudinal bunch distribution



Space charge induced spread



Space charge is compensated

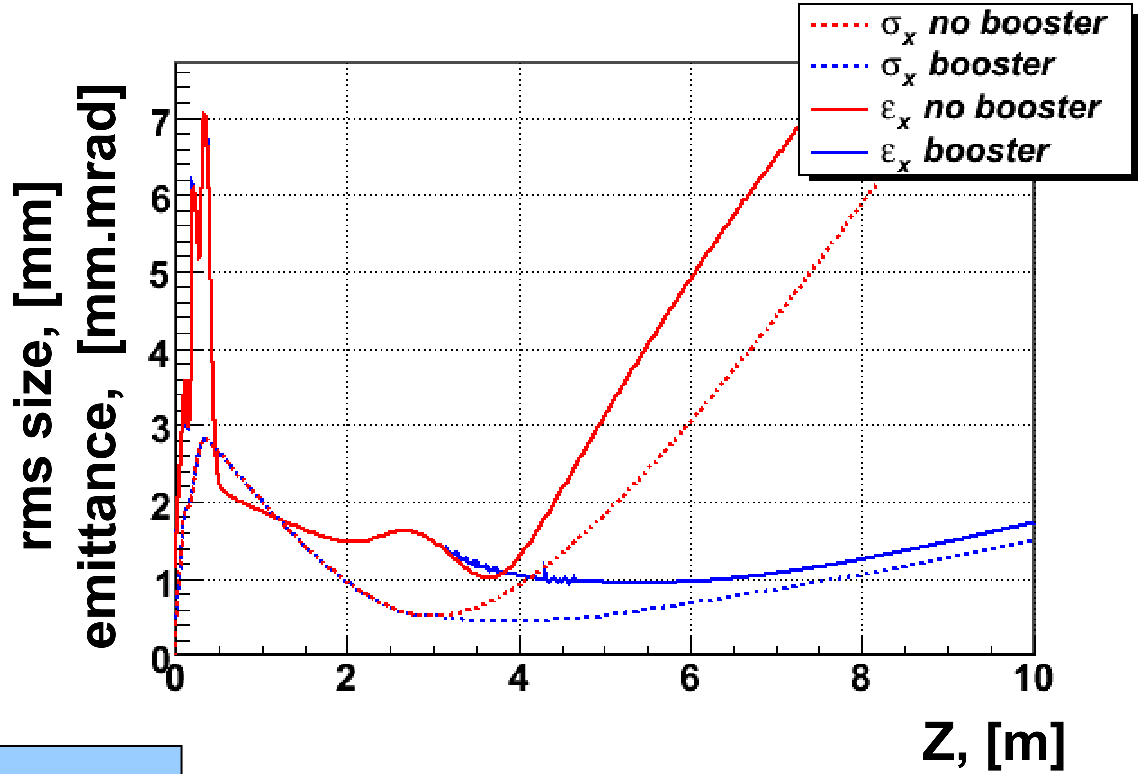


Envelope equation:

$$\sigma_\perp'' + \sigma_\perp' \frac{\gamma'}{\gamma} + \sigma_\perp \frac{\Omega^2 \gamma'^2}{\gamma^2} - \frac{I}{\sigma_\perp 2 I_A \gamma^3} - \frac{\varepsilon_{n,\perp}^2}{\sigma_\perp^3 \gamma^2} = 0$$

Emittance conservation
booster, invariant envelope

- when space charge and external focusing ratio equals beam rms
  - invariant envelope
  - emittance oscillation damped
  - beam size better contained

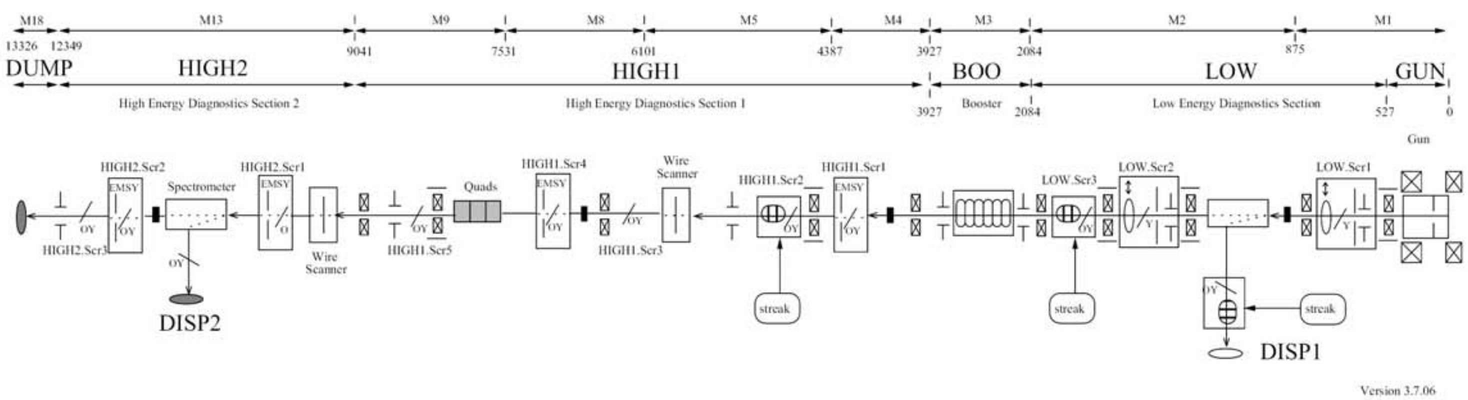


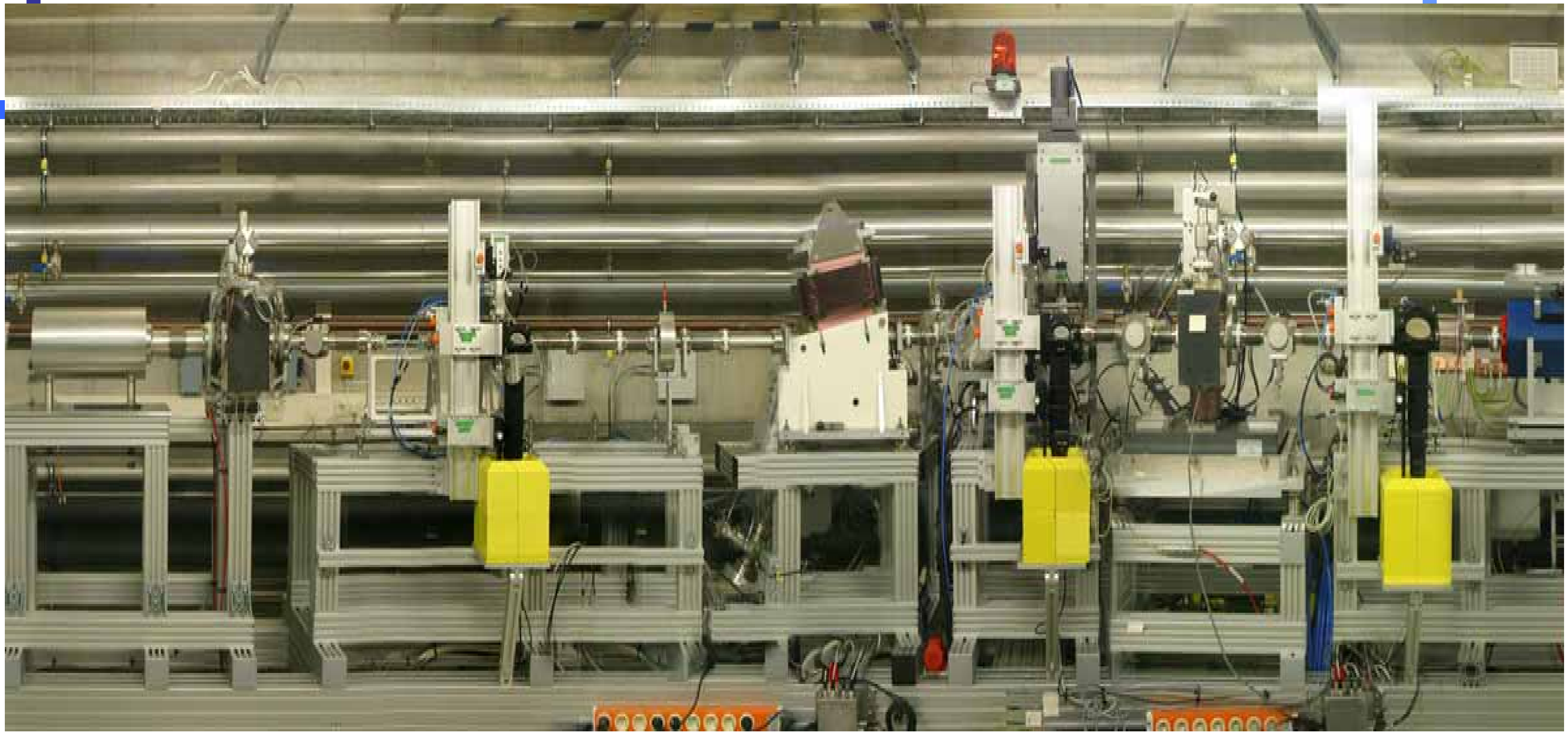
Envelope equation:

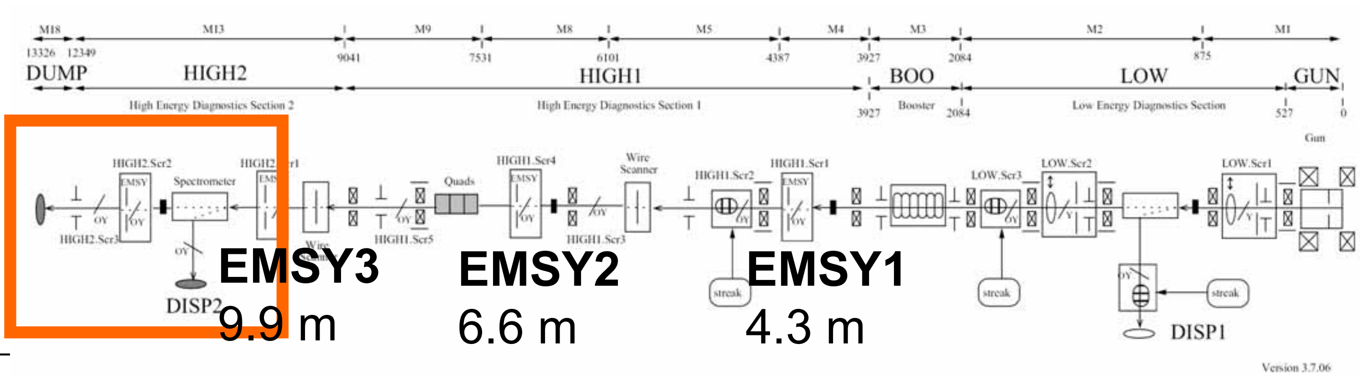
$$\sigma_\perp'' + \sigma_\perp' \frac{\gamma'}{\gamma} + \sigma_\perp \frac{\Omega^2 \gamma'^2}{\gamma^2} - \frac{I}{\sigma_\perp 2 I_A \gamma^3} - \frac{\varepsilon_{n,\perp}^2}{\sigma_\perp^3 \gamma^2} = 0$$

PITZ
diagnostic components

- Bunch charge
  - ICT and FC
- Transverse phase space
  - YAG and OTR screens
  - slit masks
- Momentum and momentum spread
  - two dispersive dipole magnets
- Longitudinal phase space
  - Cherenkov and OTR
  - streak camera






DUMP
HIGH2
High Energy Diagnostics Section 2
HIGH1
High Energy Diagnostics Section 1
BOO
Booster
LOW
Low Energy Diagnostics Section
GUN
Spectrometer
Quads
Wire Scanner
DISP2
DISP1
EMSY3
9.9 m
EMSY2
6.6 m
EMSY1
4.3 m
Version 3.7.06

PITZ parameters

- Cathode laser
  - 1 to 800 bunches per train @ 10 Hz rep. rate, 1 μs bunch spacing
  - flat top micro pulse duration of 20 ps (FWHM) with 6 ps rise/fall
- Charge per bunch Q = 1 nC
  - laser energy ~1 μJ @ 262 nm wavelength
- RF frequency 1.3 GHz
  - Max accelerating gradient 60 MV/m at the cathode
  - pulse duration 900 μs with repetition 10 Hz
- Max. mean momentum P = 14.5 *MeV/c* (32 expected)
- Bunch length FWHM ~20 ps (I_p ~ 50 A)
- Transverse normalized emittance ε_n
  - better than 0.9 mm.mrad !!!

Control parameters

red – variable parameter
blue – fixed, numerically optimized
grey – fixed, by the state of the art

0. Photo cathode laser
   - Transverse shape and size
   - Longitudinal distribution – fixed (limited tuning)

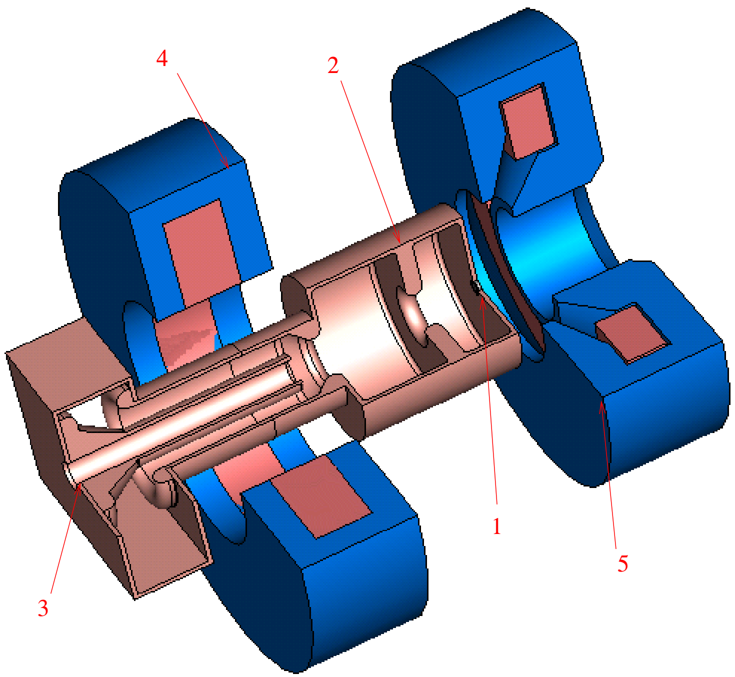
1. Cs_2Te photo cathode

2, 3. RF gun cavity, RF coupler
   - Amplitude and phase of the RF wave

4, 5. Focusing solenoids
   - focusing strength of the main solenoid (I_{main}), the other compensates I_{main}

Drift space
   - fixed - numerically optimized

Booster cavity
   - Amplitude and phase of the RF wave



Emittance measurement
methods – definition reminder

$$\Sigma_x = \begin{pmatrix} \langle x^2 \rangle & \langle xx' \rangle \\ \langle xx' \rangle & \langle x'^2 \rangle \end{pmatrix}$$

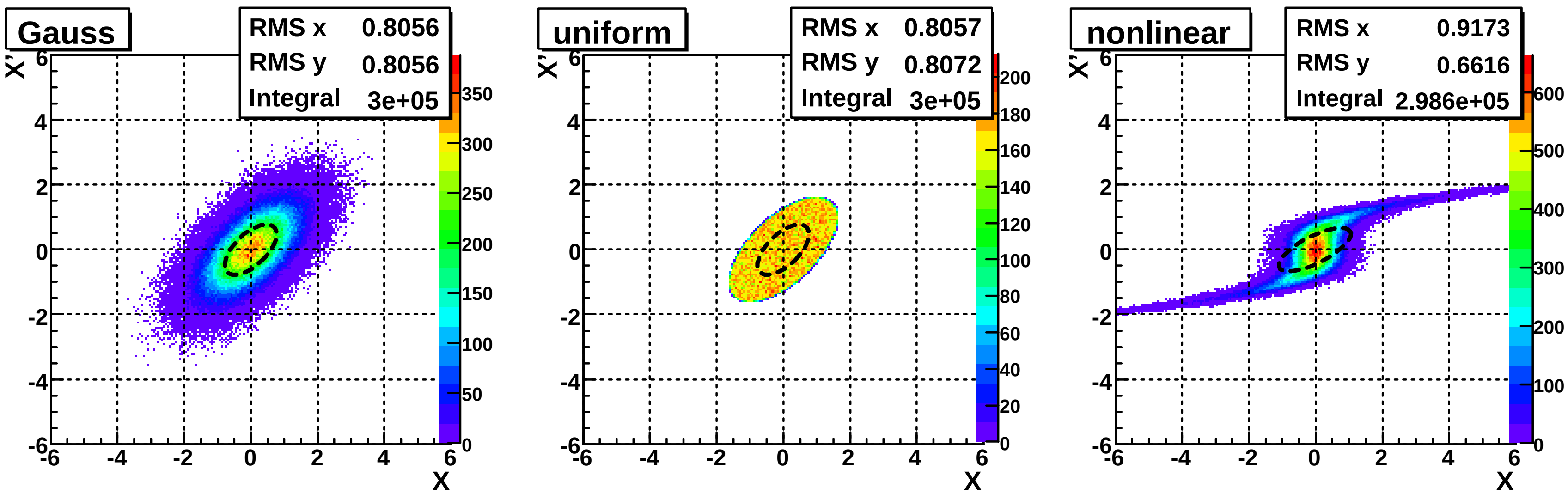
← covariance matrix

$$\det|\Sigma_x| = \varepsilon_{rms}^2$$

$$\det|\Sigma_x| \cdot \beta\gamma = \varepsilon_{rms,n}^2$$

RMS normalized emittance:

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



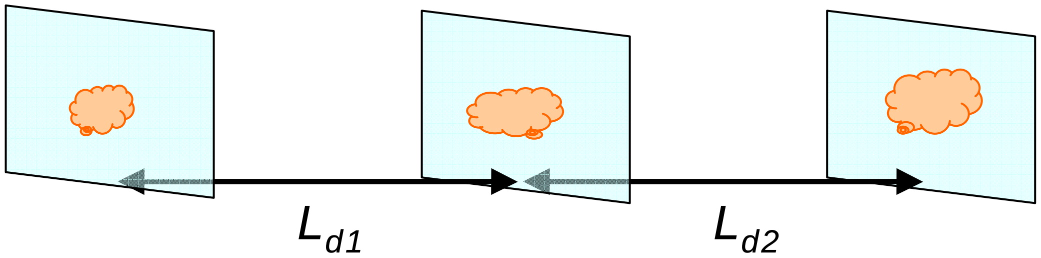
Emittance measurement

methods

transfer matrix methods

- Multiple screen method

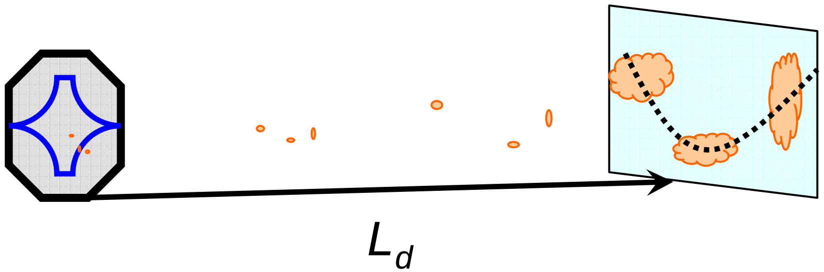
$$\Sigma_x^n = R \cdot \Sigma_x^{n-1} \cdot R^T;$$



- Quadrupole scan technique

$$\sigma_x^2(z) = \left[\sigma_{x0}^2 - 2\alpha_{x0}\varepsilon_x L_d + \gamma_{x0}\varepsilon_x L_d^2\right] + \frac{2\sigma_{x0}^2}{f}\left[\frac{\alpha_{x0}}{\beta_{x0}} L_d - L_d\right] + \frac{2\sigma_{x0}^2}{f^2} L_d;$$

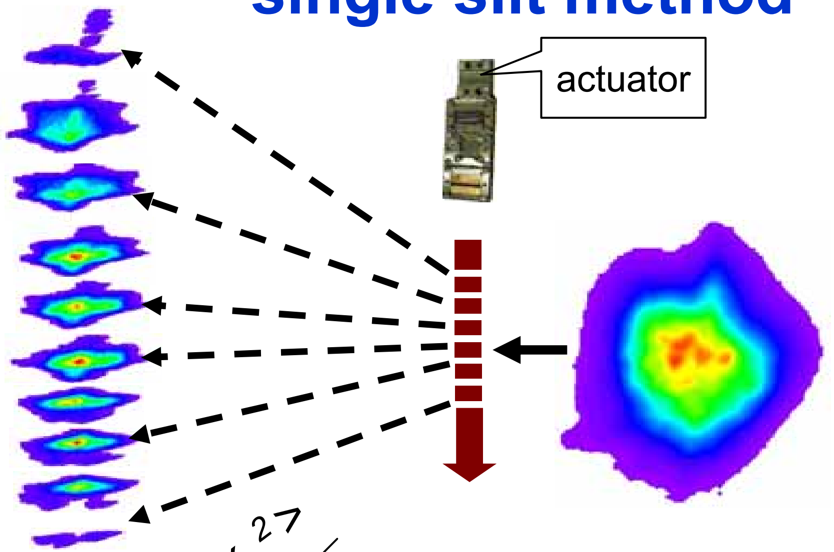
here: α, β, γ – are the Twiss parameters; f – the quadrupole focusing strength



Emittance measurement

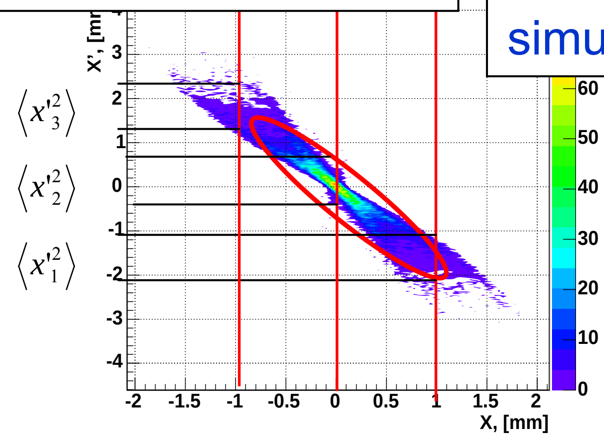
methods

single slit method



Automatic measurement proc.

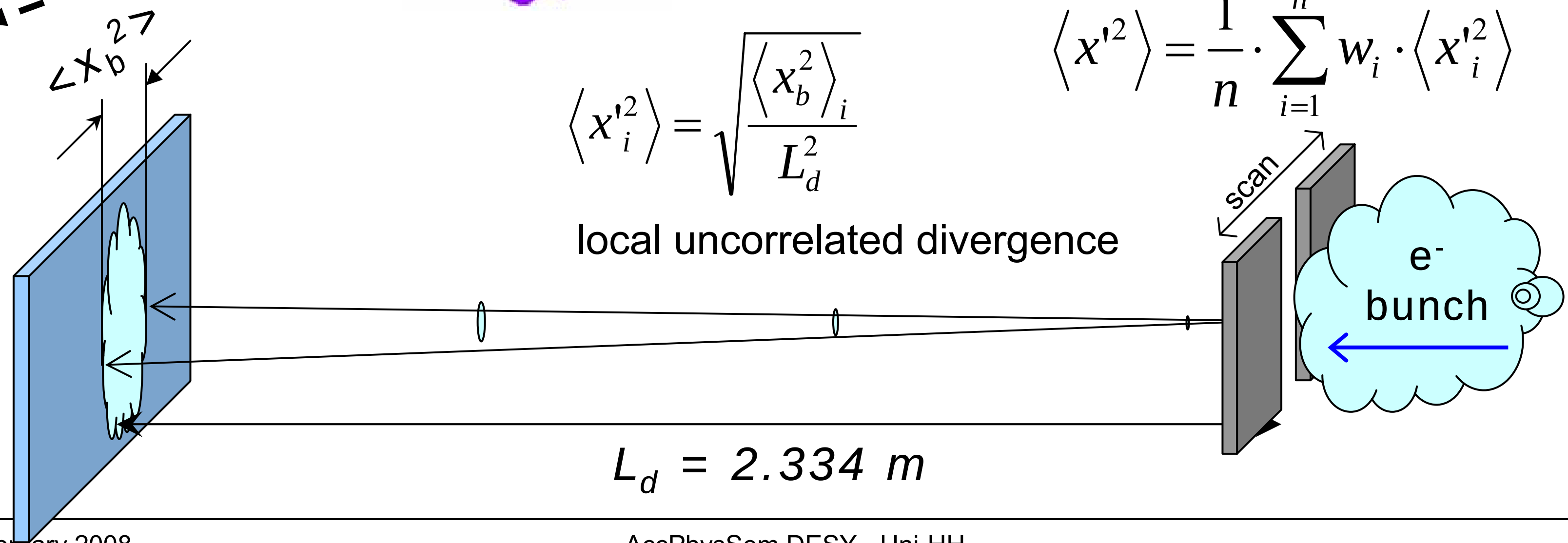
ASTRA simulation



$$\langle x'^2 \rangle = \frac{1}{n} \cdot \sum_{i=1}^{n} w_i \cdot \langle x'^2_i \rangle$$

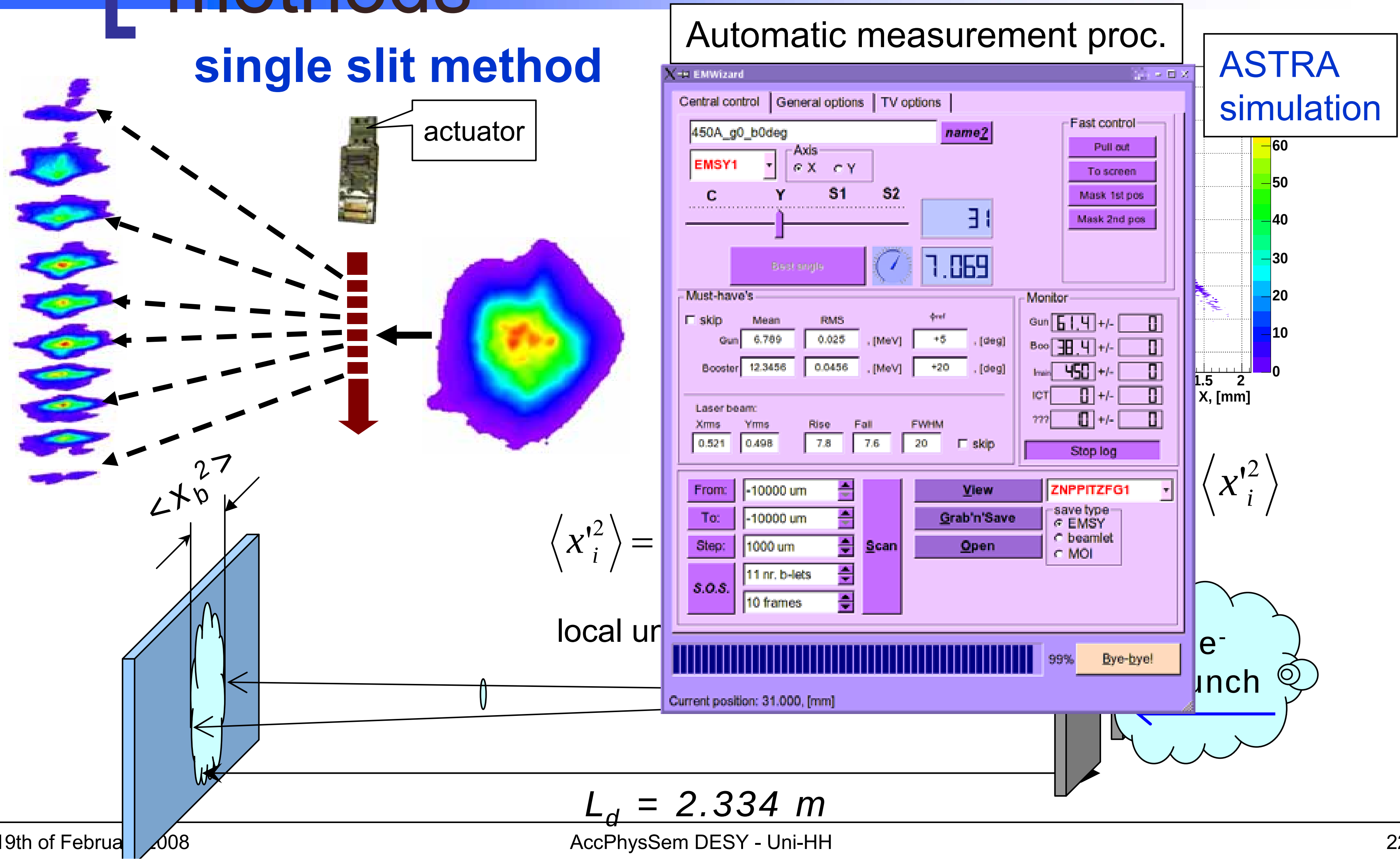
$$\langle x'^2_i \rangle = \sqrt{\frac{\langle x_b^2 \rangle_i}{L_d^2}}$$

local uncorrelated divergence



Emittance measurement methods

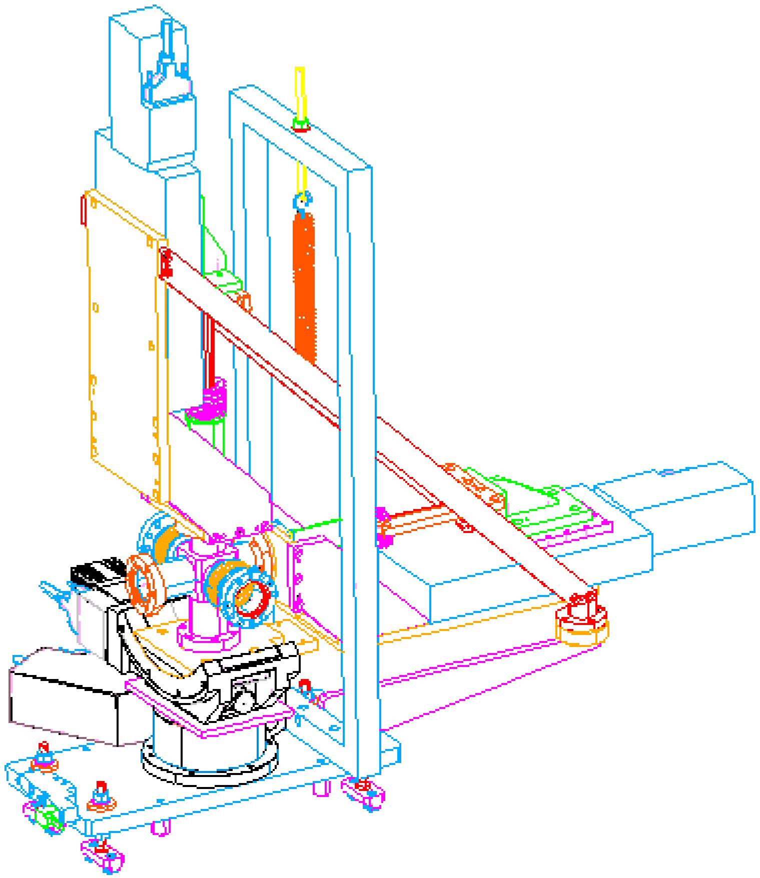
single slit method



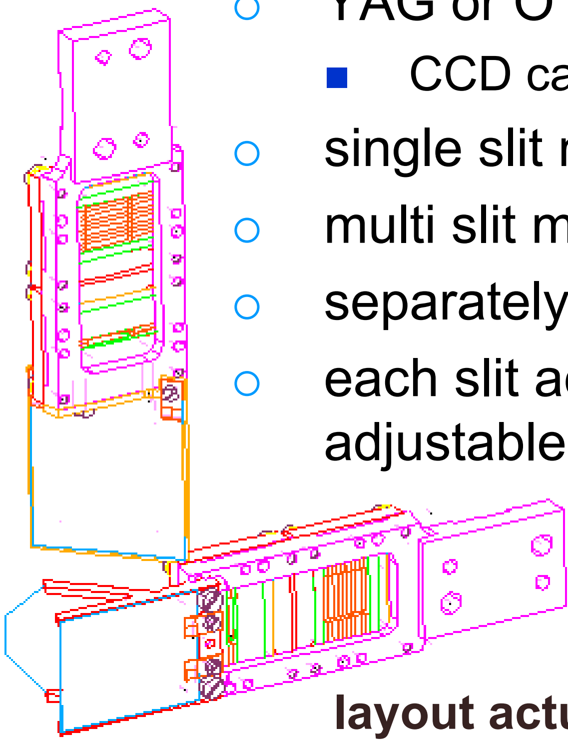
Slit method
general requirements

- Emittance dominated beamlets (slit opening)
  - Reliable signal from the beamlets
- The mask thickness must be enough to scatter the residual electrons
- Optimal drift length
  - enough distance for beamlet evolution (max. L_d)
    - resolution of the divergence
    - elimination of the influence from the initial beamlet size
  - minimizing the effect of space charge (min. L_d)

Emittance Measurement SYstem (EMSY)



EMSY layout



layout actuators

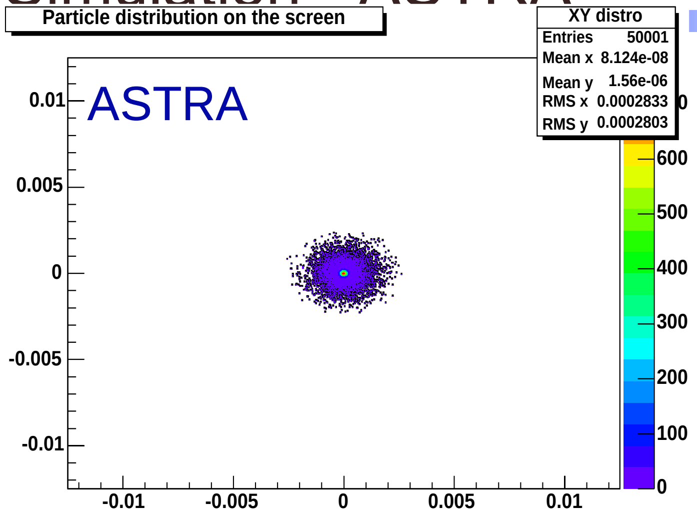
- two orthogonal actuators
  - YAG or OTR screen
    - CCD camera
  - single slit mask
  - multi slit mask
  - separately movable
  - each slit acceptance adjustable

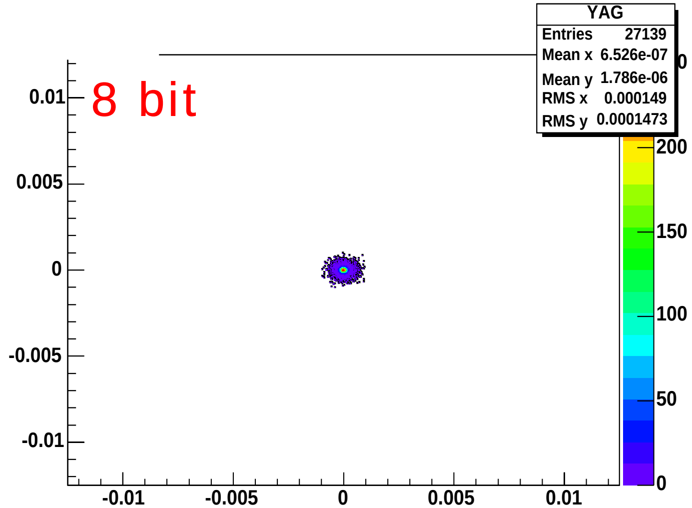
Emittance Measurement: Systematic uncertainty

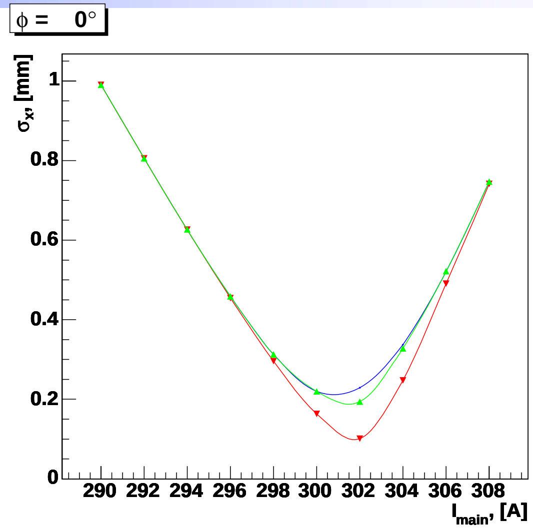
- beam size measurements
  - screen
    - saturation (YAG), screen geometry, multiple scattering etc.
  - optic lenses
  - CCD camera
- local divergence
  - beamlet size measurements
  - space charge contribution
  - noise from scattered electrons
- momentum measurements
  - dipole field errors
  - beam size associated

Electron beam size measurement

Simulation - ASTRA







- 768x567 CCD chip
- Screen area 20x20 mm
- ASTRA –
  - 750k particles, 1 nC
  - gun only.
  - Beam momentum ~ 5 MeV
  - **8 bit – 1/255**
  - **12 bit – 1/4096**

Emittance Measurement uncertainty
Space charge effect

- Envelope equations for non-symmetric beam
  - Used to calculate the beamlet evolution
  - Estimates the influence of the slit opening due to space charge on the beamlet size
- Uniform distribution used to solve the system

- General parameters:
  - I = 50, A
  - γ = 10 .. 60
  - σ_x = 0.2 .. 2, mm
  - σ'_x - scaled such that
  - ε_x = 1 mm.mrad

Emittance Measurement uncertainty
Space charge effect

- Envelope equations used

$$\sigma_x'' = \frac{I}{I_a \cdot (\sigma_x + \sigma_y) \cdot \gamma^3} + \frac{\varepsilon_{nx}}{\sigma_x^3 \cdot \gamma^2}$$

$$\sigma_y'' = \frac{I}{I_a \cdot (\sigma_x + \sigma_y) \cdot \gamma^3} + \frac{\varepsilon_{ny}}{\sigma_y^3 \cdot \gamma^2}$$

here:

I - peak current [A], I_A - Alfven current (17.0 kA);
σ_x - transverse size; σ'_x - transverse divergence;
ε_x - normalized emittance; γ - Lorentz factor;

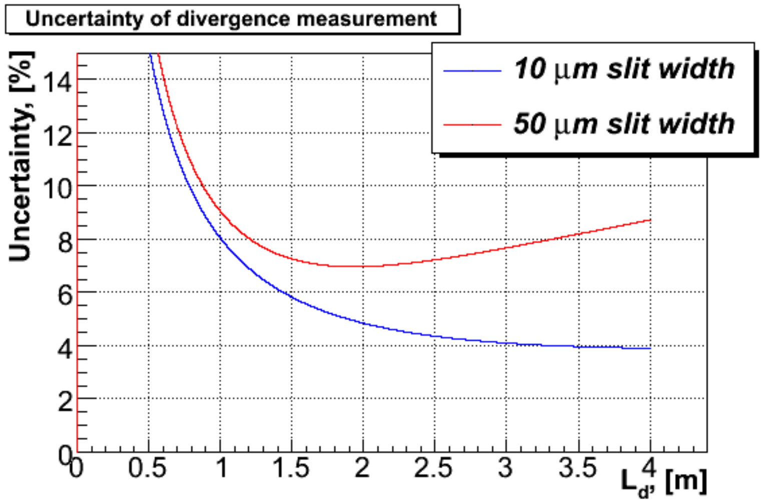
$\langle xx' \rangle$ - for now it is assumed to be zero

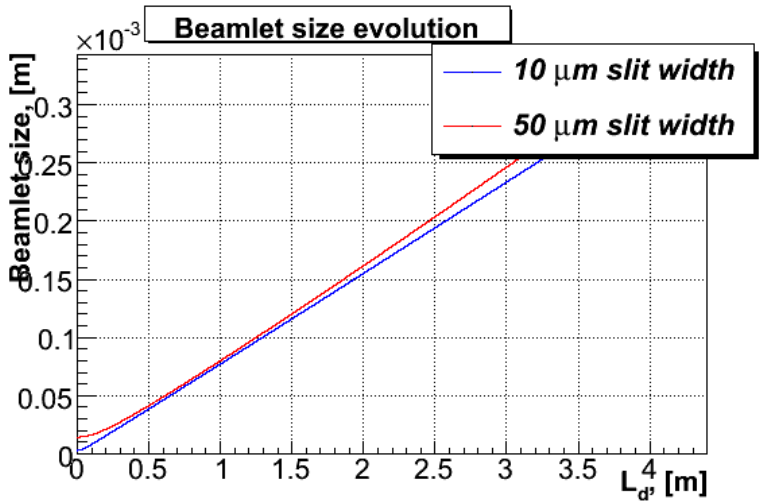
- General parameters:
  - I = 50, A
  - γ = 10 .. 60
  - σ_x = 0.2 .. 2, mm
  - σ'_x - scaled such that
  - ε_x = 1 mm.mrad

Emittance uncertainty
nominal values at **30 MeV/c**

- Asymmetric envelope equations solved for:
  - I = 50 A
  - **γ = 58.7 (30 MeV/c)**
  - σ_0 = 0.2 mm
  - σ'_x = 0.0766 mrad
  - **ε_x = 0.9 mm.mrad**
- Optical resolution of **50 lines/mm**

- Uncertainty at ***L_d = 2 m***
  - **4.85 % (10 μm slit)**
  - 155 μm beamlet rms size

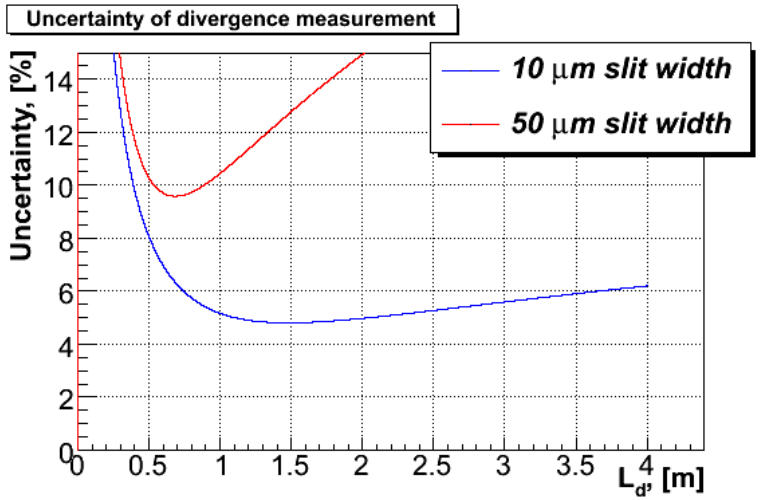


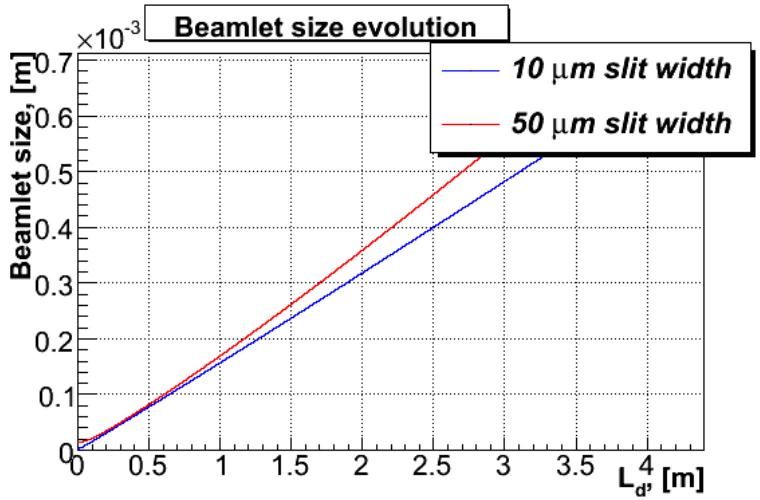


Emittance uncertainty

nominal values at **15 MeV/c**

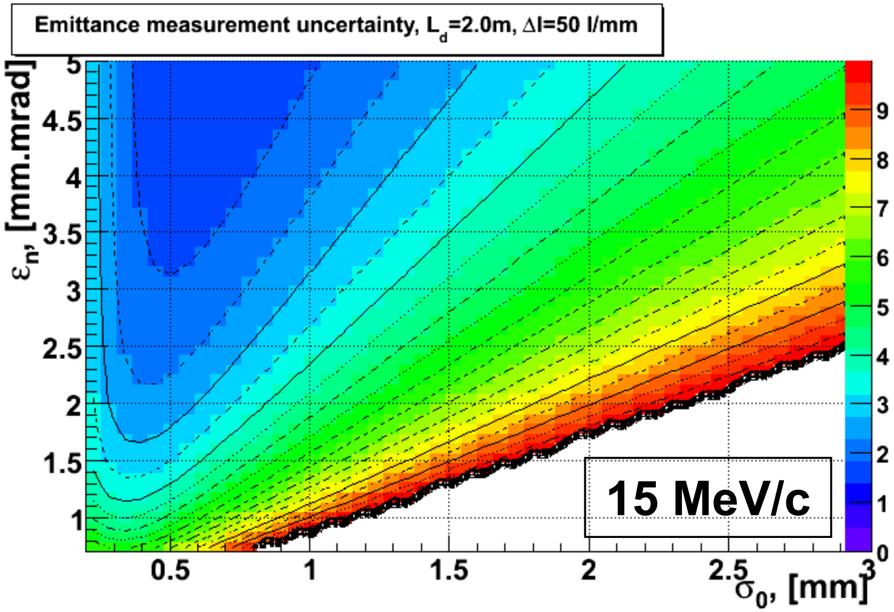
- Asymmetric envelope equations solved for:
  - I = 50 A
  - **γ = 29.3 (15 MeV/c)**
  - σ_0 = 0.2 mm
  - σ'_x = 0.153 mrad
  - **ε_x = 0.9 mm.mrad**
- Optical resolution of **50 lines/mm**
- Uncertainty at ***L_d = 2 m***
  - **4.98 % (10 μm slit)**
  - 318 μm beamlet rms size



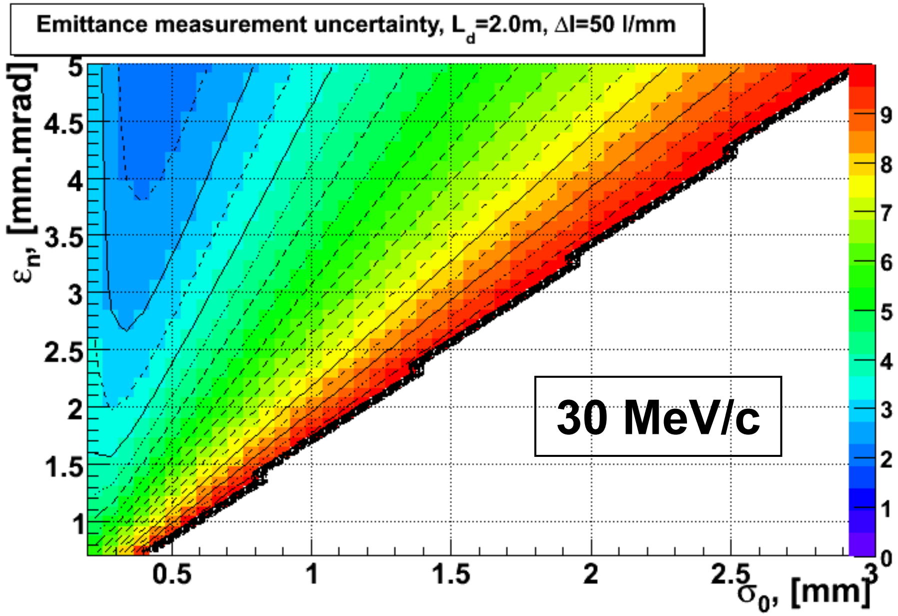


Emittance uncertainty

error map



- Here:
  - I = 50, A
  - σ_0 = variable, mm
  - σ'_x - scaled to correspond
  - ε_x = variable, mm.mrad

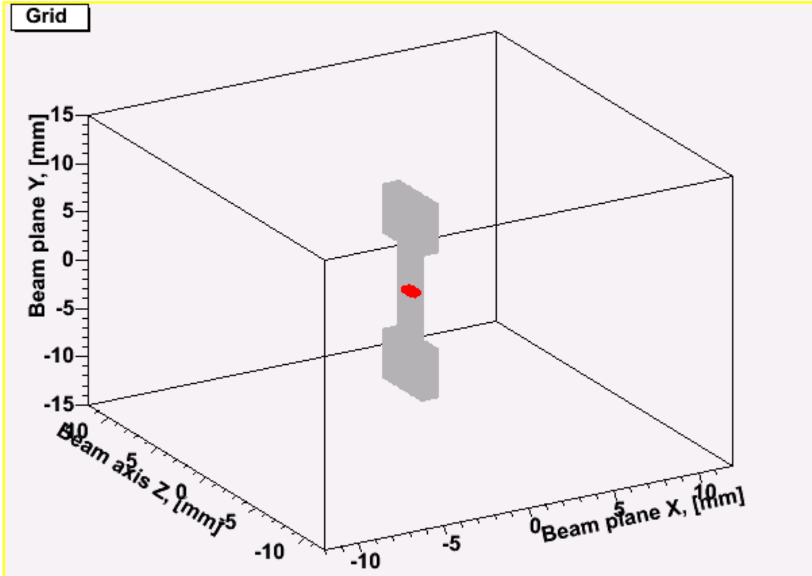


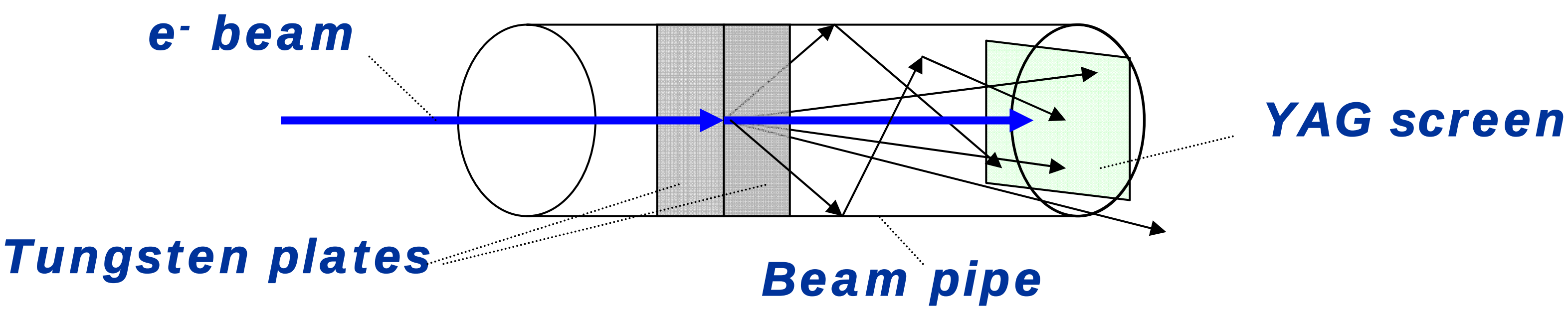
- Uncertainty map
  - ***L_d = 2 m***
  - ***10 μm slit opening***
  - ***50 lines/mm***

GEANT4 simulations

slit mask

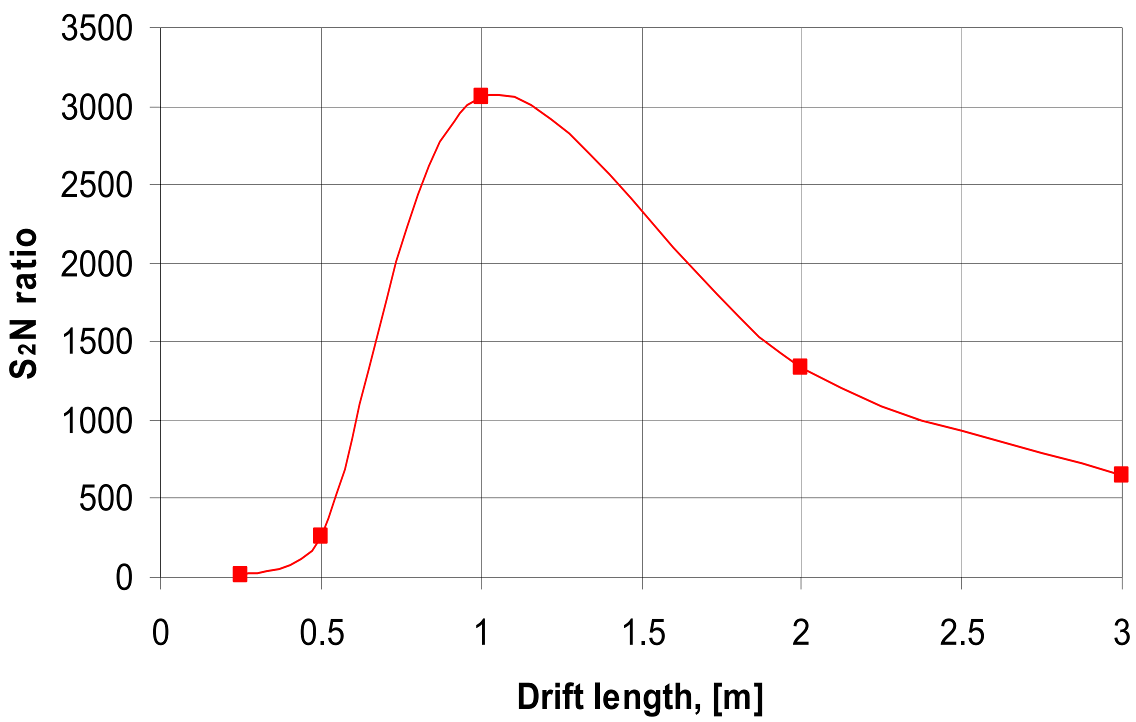
- Simplified G4 model
  - The signal to noise ratio
  - The energy deposited in the tungsten
- The plate thickness, the distance to the screen and used as variables





GEANT4 simulations

signal to noise ratio



$$S2N = \frac{C_s}{C_n} \cdot \frac{A_n}{A_s}$$

Here:

- C_s – *counts signal*
- C_n – *counts noise*
- A_s – *area of the signal*
- A_n – *area of the noise*

Slit parameters:

- ***Tungsten***
- ***1 mm thickness***
- ***10 μm slit opening***

EMSY optimization
Conclusions

- The slit mask material is chosen to be Tungsten
- The thickness of the slit mask must be 1 mm
- The slit opening should be 10 μm
- Distance (L_d) between the screen and the mask ~ 2 m
- 12 bit camera resolution is required
- optical resolution better than 50 $lines/mm$

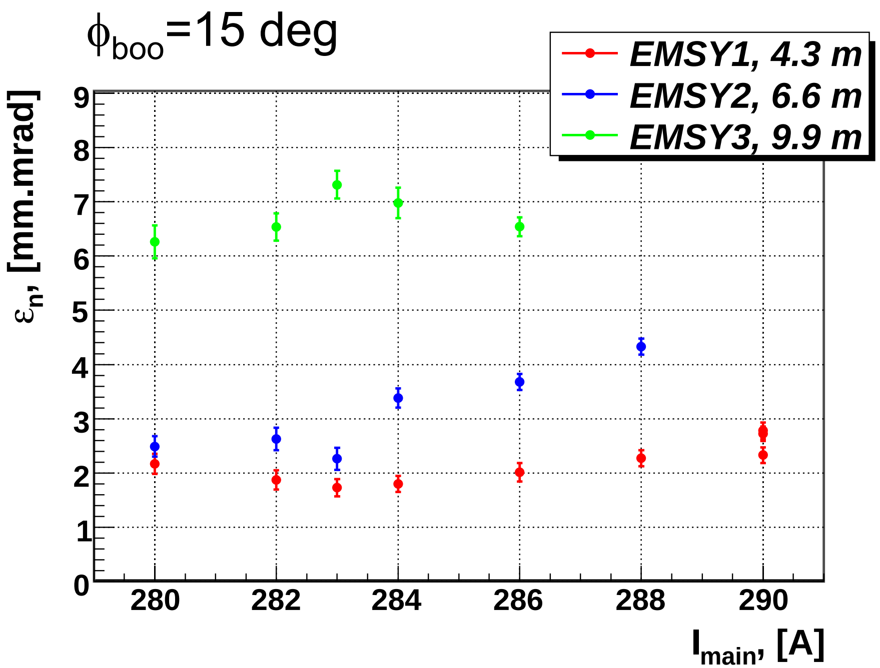
Emittance measurements

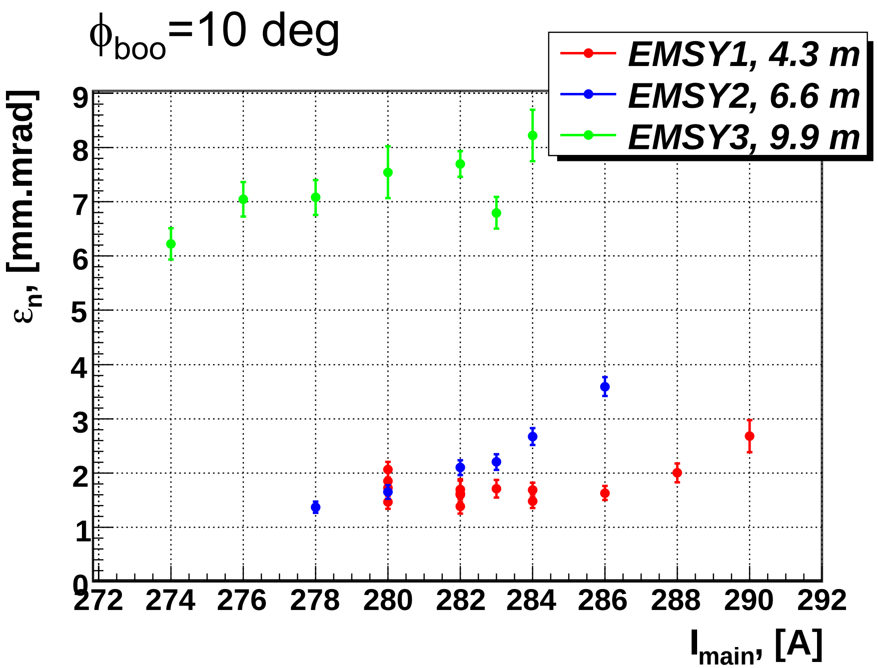
Two different gun cavities of the same prototype

- gun 3.1 (October 2006)
  - max. gradient ~43 MV/m (FLASH spare gun)
  - optimization parameters:
    - I_{main} around the focus at EMSY screen
    - booster phase (phase of the gun fixed ϕ_0+2)
    - emittance measured at three locations downstream
  - only 8 bit cameras used
- gun 3.2 (August 2007)
  - max. gradient ~60 MV/m (1st test for XFEL gun)
  - optimization parameters:
    - I_{main} scanned around the focus at EMSY screen
    - booster accelerating gradient (phases of gun ϕ_0 and booster ϕ_0 are fixed)
    - different initial beam sizes at the cathode
  - 12 bit cameras used for beamlet measurements

Emittance measurements
gun 3.1 (October 2006)

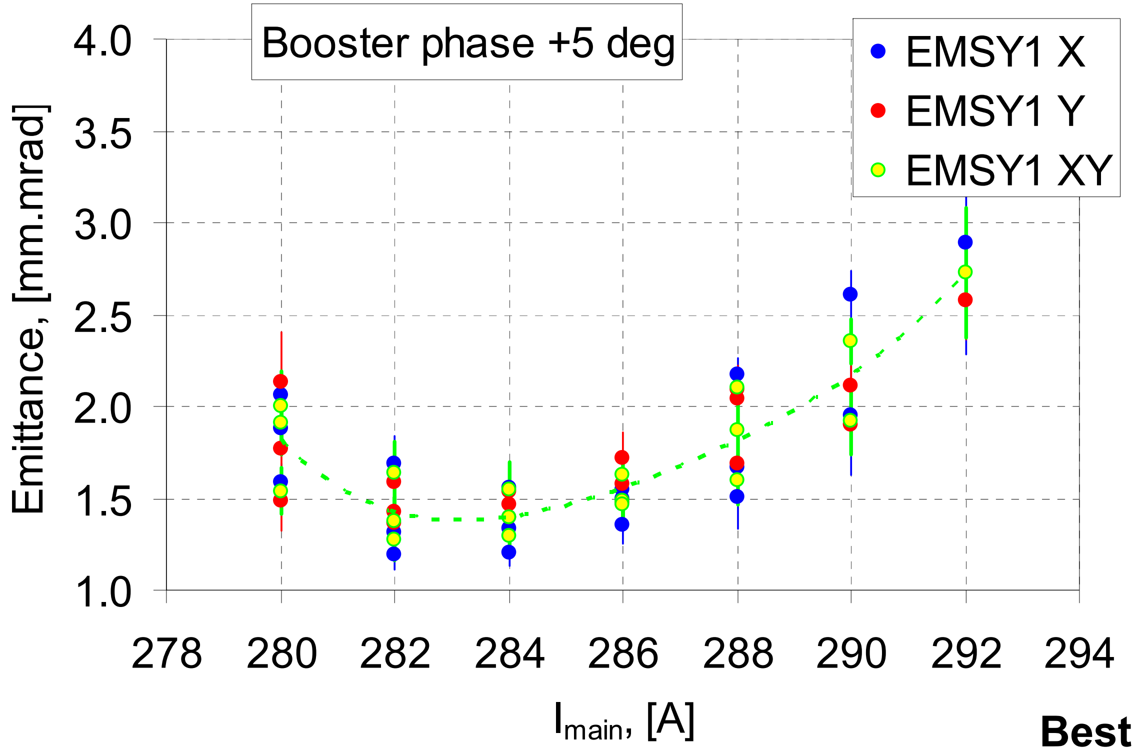
- Gun gradient ~43 MV/m (at the cathode)
- Final beam momentum ~ 13 MeV/c
- Laser rms spot size ~ 0.51 mm





Emittance measurements

gun 3.1 (October 2006)



Measurement conditions:

mean momentum MeV/c

~ 4.95 @ gun

~ 13.0 @ booster

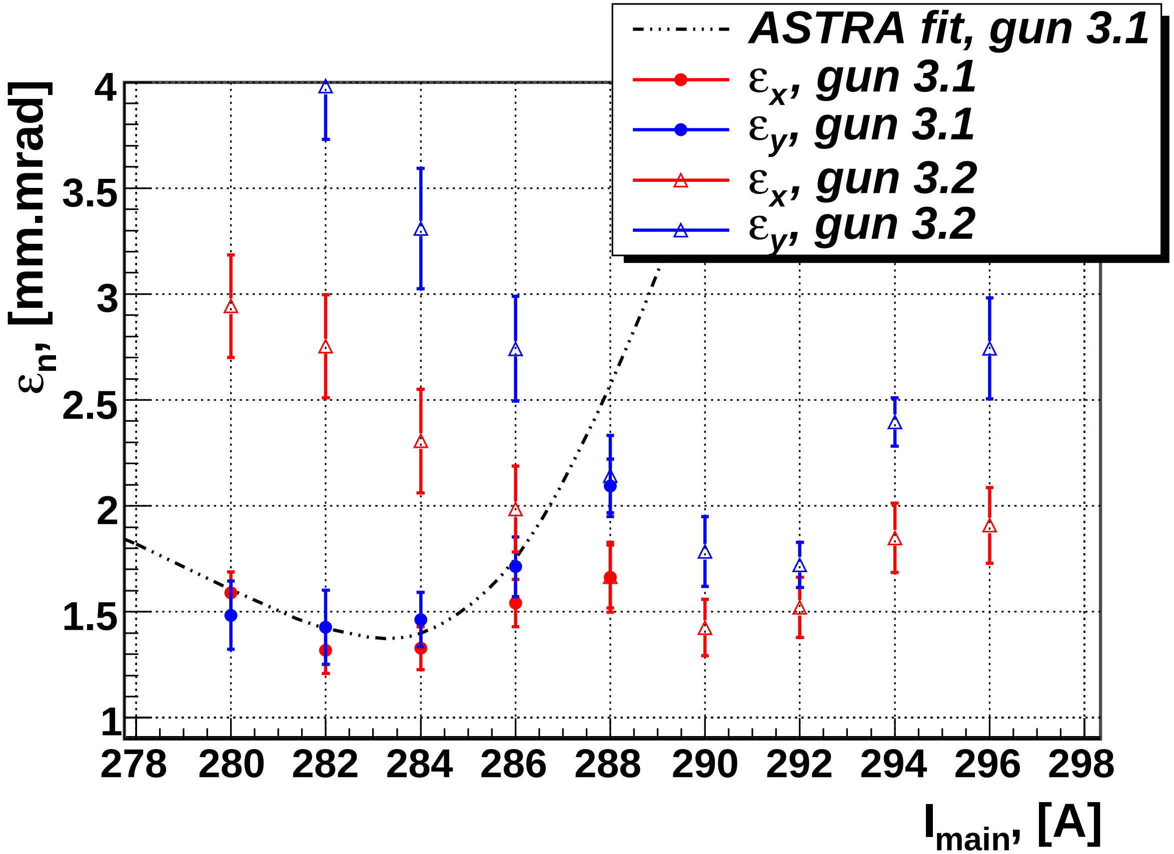
initial rms spot size ~ 0.51 mm

Best measurement taken:

I_{main}	=	282	[A]
ε_x	=	1.32±0.11	[mm mrad]
ε_y	=	1.43±0.17	[mm mrad]

Emittance measurements

Comparison – gun 3.1 vs. gun 3.2



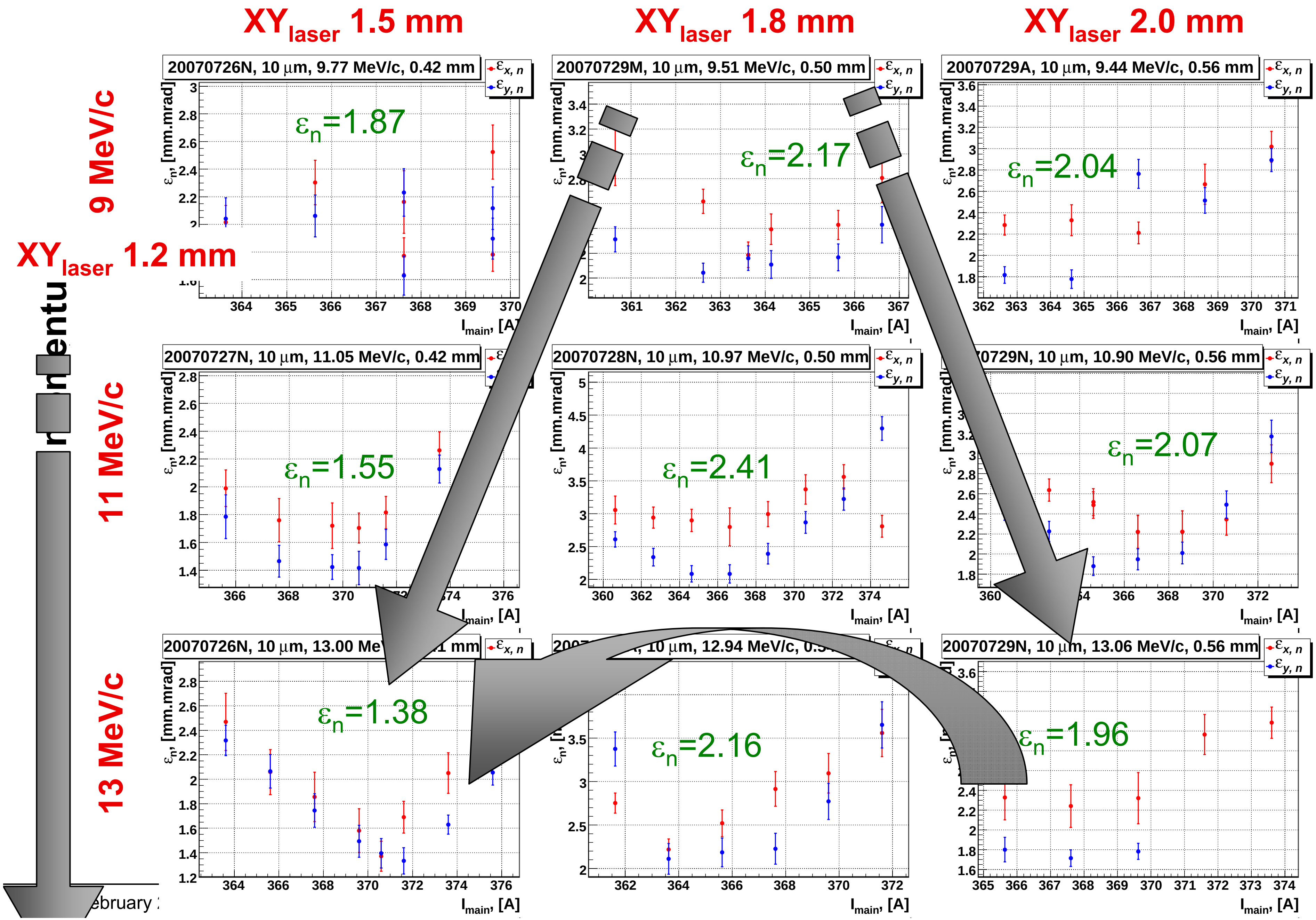
- Machine parameters:
  - XY_{ini}=0.51 mm (rms laser@cath)
  - mean momentum MeV/c
    - gun 4.95
    - booster 12.85
      - $\phi_{booster}=\phi_0$+5 deg
- Minimum emittance:
  - gun 3.1
    - ε_{xy}=1.37±0.14 mm.mrad
    - I_{main}=282 A (0.166 T)
  - gun 3.2
    - ε_{yy}=1.54±0.15 mm.mrad
    - I_{main}=290 A (0.171 T)
- beamlet observation CCD cameras different (8 & 12 bit)

Emittance measurements

gun 3.2 (August 2007)

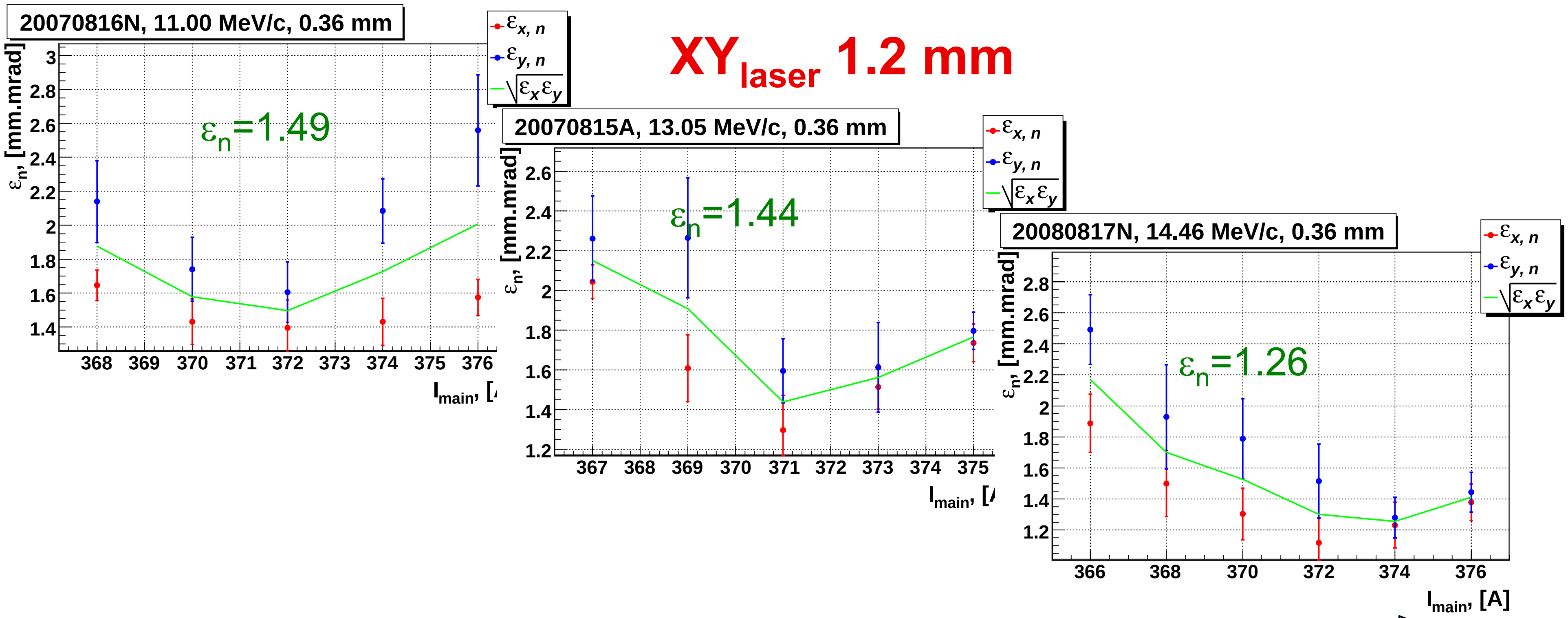
- EMSY1 only
- fixed phases @max. momentum gain
- gun gradient ~ **60 MV/m@cathode**
- different laser diameter at cathode
  - Laser aperture (**XY_{laser}**) - **1.2, 1.5, 1.8** and **2.0** mm
  - rise/fall time ~ 6 ps
  - FWHM ~ 20 ps
- different booster gradients
  - final beam momentum of **9.5, 11, 13** and **14.5** MeV/c

Emittance measurements, gun 3.2 (August 2007)



Results

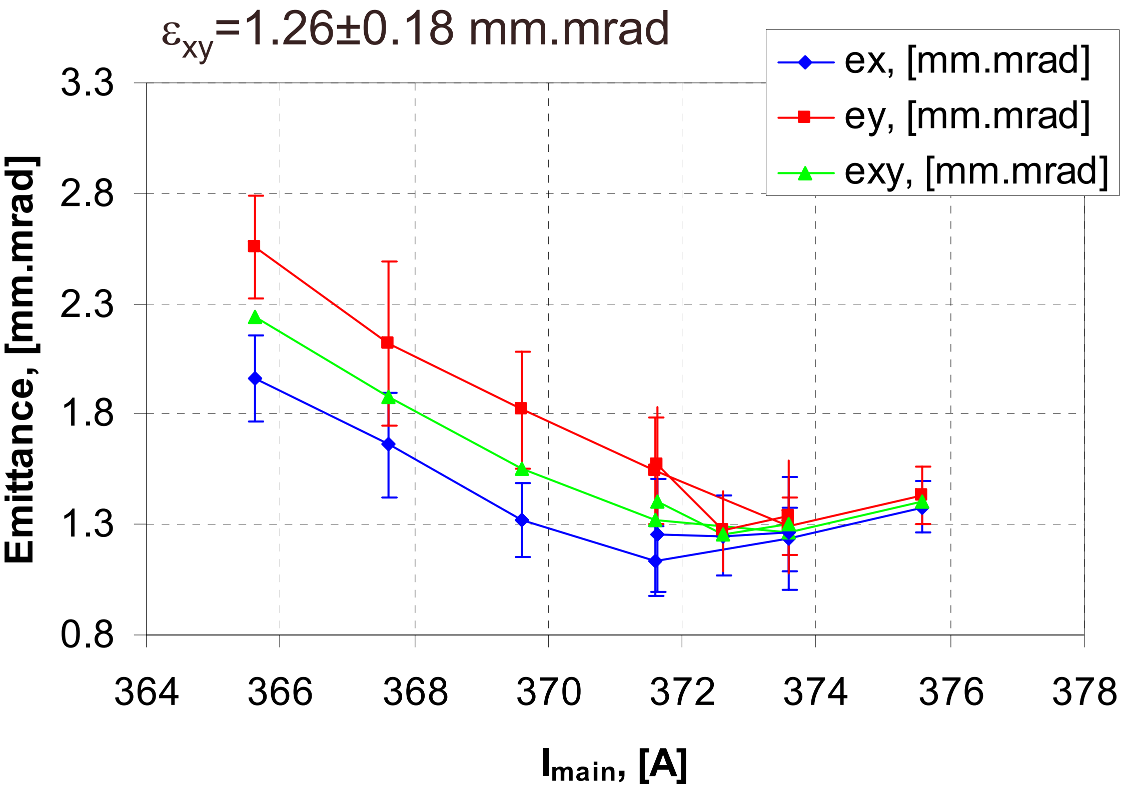
gun 3.2 (August 2007)



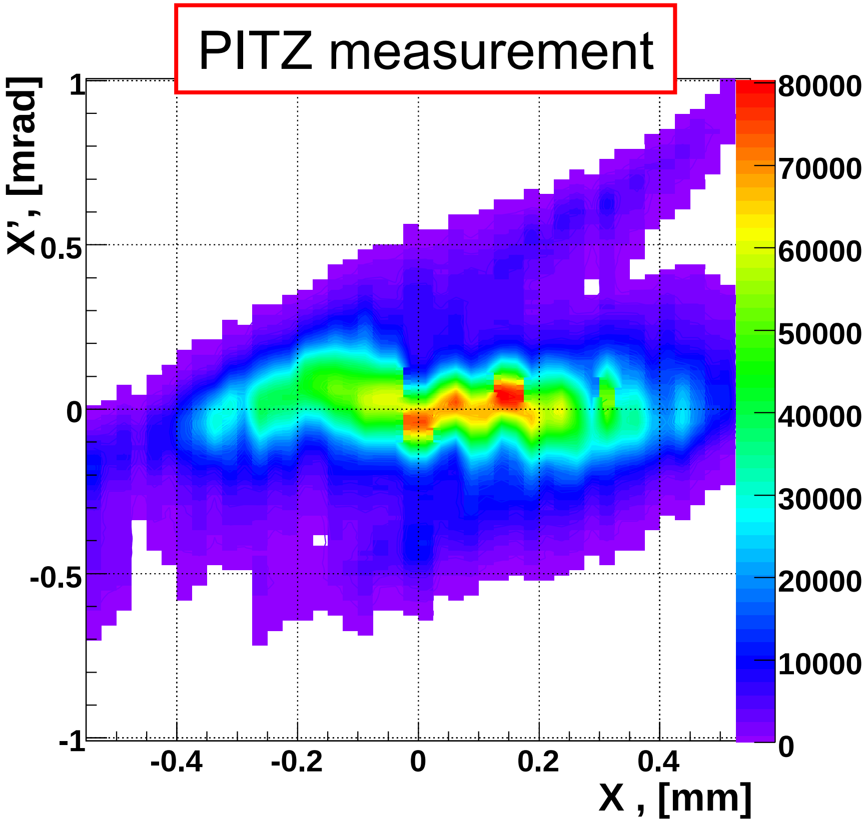
P_{mean}=11, P_{mean}=13, P_{mean}=14.5, [MeV/c]

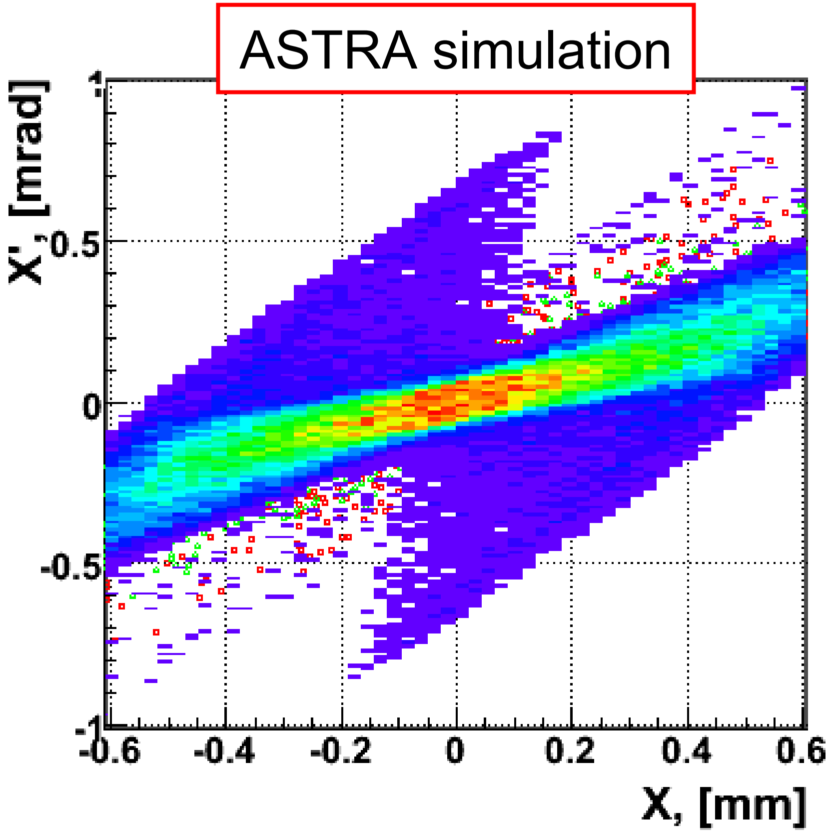
Results
best emittance

- Measurement conditions:
  - Laser
    - XYini=0.36 mm (rms)
    - rise/fall time 6 ps
    - FWHM = 20 ps
  - Maximum gradient ~60 MV/m
  - Gun and booster phases at max. momentum gain
    - P_{gun}=6.44 MeV/c
    - P_{boo}=14.46 MeV/c
  - minimum emittance measured at I_{main} = 374 A (-0.220 T)



Results
best emittance – phase space





- measured phase space distribution
  - XYini=0.36 mm (rms)
  - P_{boo}=14.46 MeV/c
  - I_{main} = 374 A (-0.220 T)

Summary and outlook

- PITZ is capable of producing electron beams with small emittance
  - the smallest value achieved was ε_{xy}=1.26±0.18 mm.mrad (geom. avg.)
- Optimization of the emittance measurement system was done – slit mask, screen setup and readout system
  - wider momentum range
  - lower emittance
- Automatic measurement procedure implemented
  - faster measurements
  - more reliable results
- Main optimization parameters scanned
  - Solenoid strength
  - initial beam size
  - booster gradient

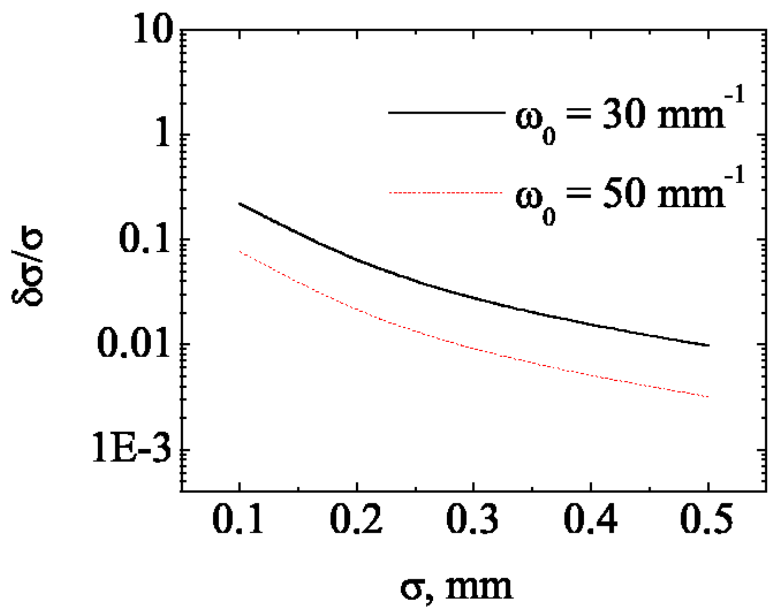
- To be improved:
  - differences between gun3.1 and gun3.2 have to be understood
- upgrade of the laser system is ongoing
  - 2 ps rise/fall times (XFEL milestone)
- in 2008 new booster cavity will be installed
  - improved stability
  - better field quality
  - more flexibility for studying the invariant envelope matching principle

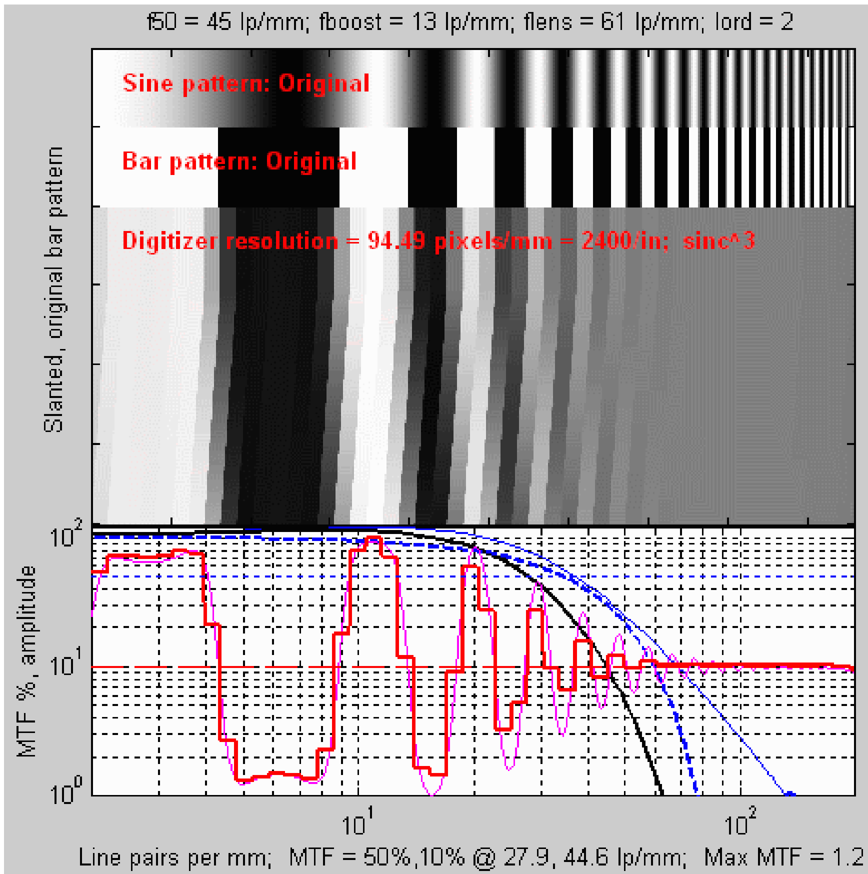
Thank You for the attention!

Electron beam size measurement

optics contribution

- MTF formalism used
- Uncertainty as a function of beam size

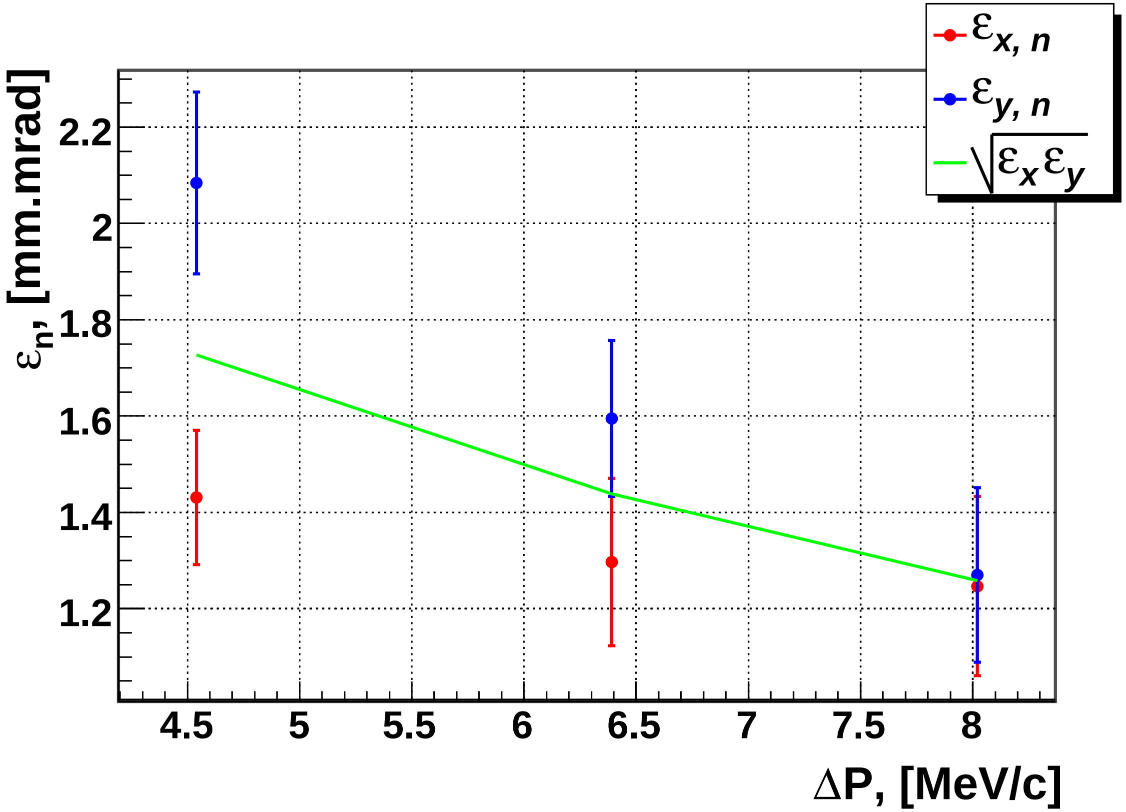




http://www.normankoren.com/Tutorials/MTF.html

Results

gun 3.2 (August 2007)



emittance obtained for different booster momentum gain

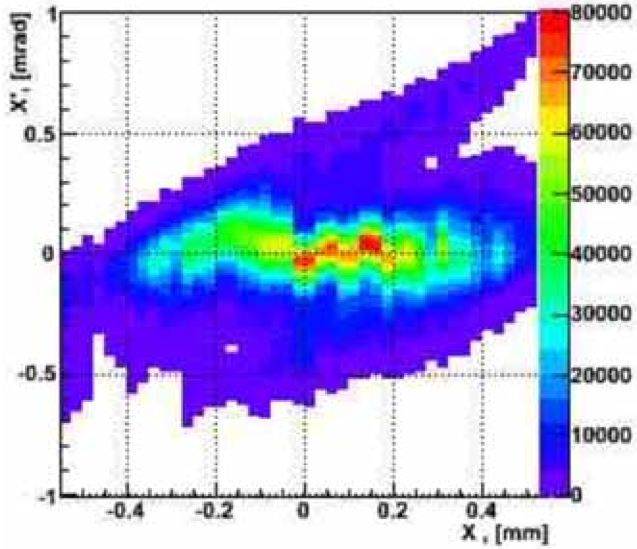
I_{main} = 374 A

XY_{laser} = 1.2 mm

Signal / Noise ↔ RMS ↔ Core emittance

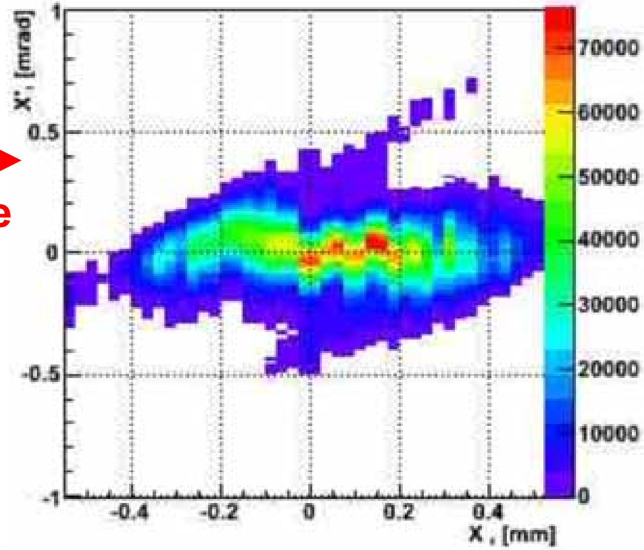
x-x´-phase space distribution for the best emittance measurement, purely reconstructed from subsequent beamlet measurements:

100 % of data



➔ ε_n=1.1 mm mrad

Cut at **5% of max. amplitude**
(i.e. 6.5% of “charge”)
[reasons: by purpose or because of noise, gain, sensitivity, bit depth, …]



➔ ε_n=0.69 mm mrad

⇨ **projected emittance is reduced by 37 % !!**

Reminder: This $\varepsilon_n \neq$ 1.25 mm mrad because the separately measured beam size at the slit position is NOT taken into account here.

ASTRA: - 5% in particles ➔ -38% in proj. emittance

For 95% RMS ➔ $\varepsilon_{x,\,y,\,n} \approx 0.8$ mm mrad