Principal limitations and systematic deviations regarding the slit measurement method

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CHBB-2008

Zeuthen, Germany, 26-30.05.2008

Outlook

- Slit scan technique for the emittance measurements
- ASTRA simulations, main solenoid scan
- Emittance calculation from slit scan data:
  - Correction term due to the phase space nonlinearity
  - Experimental data analysis
  - Beam position jitter influence
- Conclusions

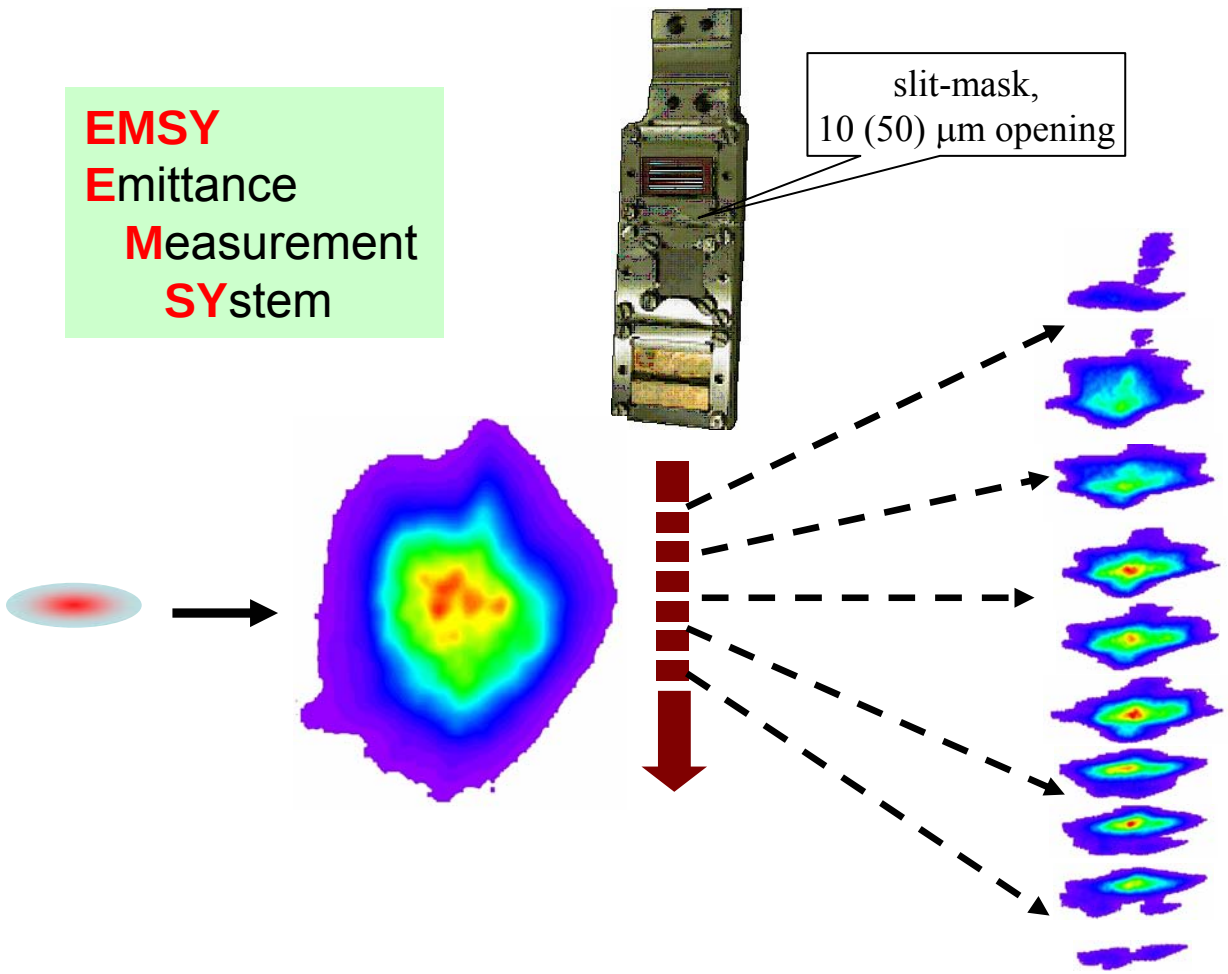
Emittance measurements using slit scan technique

$$\varepsilon_x^n = \beta\gamma \cdot \sigma_X \cdot \sigma_{X'} \Rightarrow \varepsilon_{meas0}$$

σ_X - whole beam rms size at EMSY screen (z = 4.3m)

$$\sigma_{X'} = \frac{1}{L}\sqrt{\sum_{n=1}^{Nsl} w_n \cdot \left(\sigma_{X,n}^{BL}\right)^2 \Big/ \sum_{n=1}^{Nsl} w_n}$$

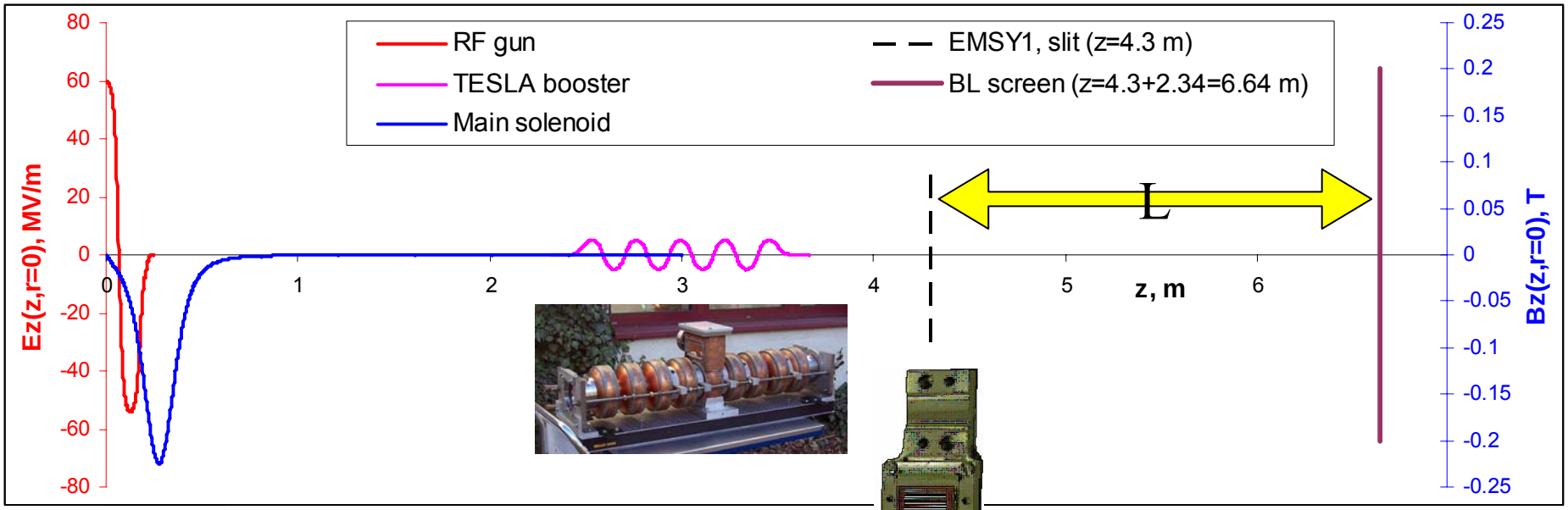
EMSY
Emittance
Measurement
SYstem

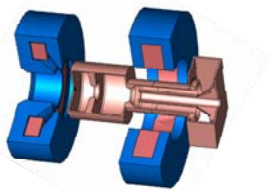


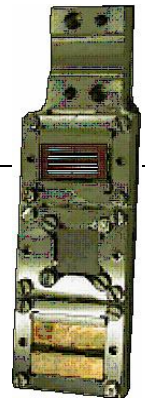
Emit.meas@PITZ

- X + Y
- Projected
- RMS
- 100%

ASTRA simulations of emittance measurements



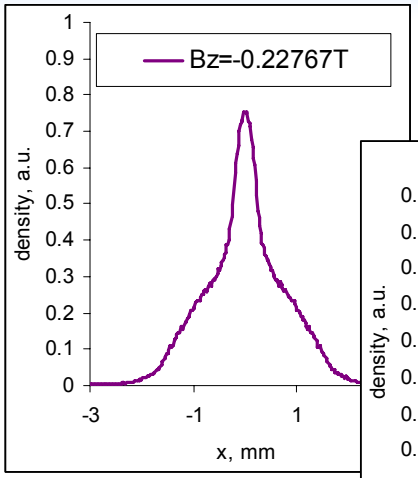


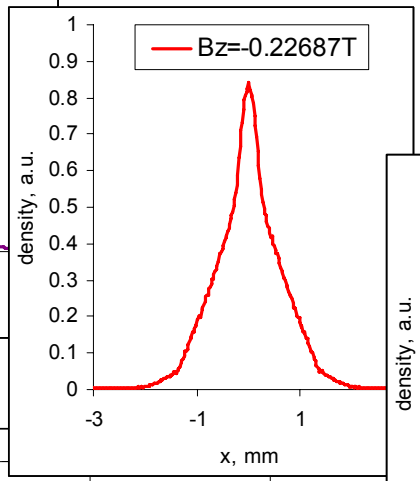


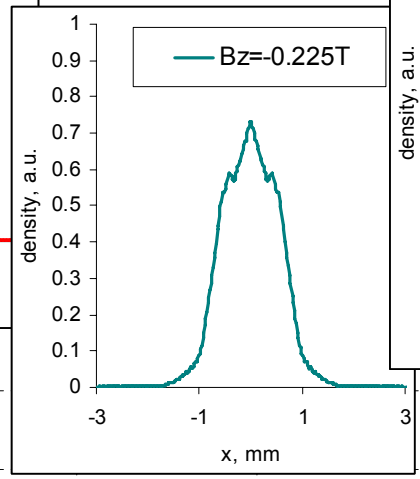
RF gun			booster	simulations
cavity	**solenoid**	**laser**	**TESLA**	**ASTRA**
Ecath=60MV/m	Bmax=-0.225T(varied)	Lt=20ps	z(center)=2.99m	200k particles
Phi=-1.1deg	zmax=0.276m	rt=5ps	Emax=5MV/m	
		XYrms=0.44mm	phi=-5.5deg	
		Ek=0.55eV		
		ThEm=0.37mm mrad		

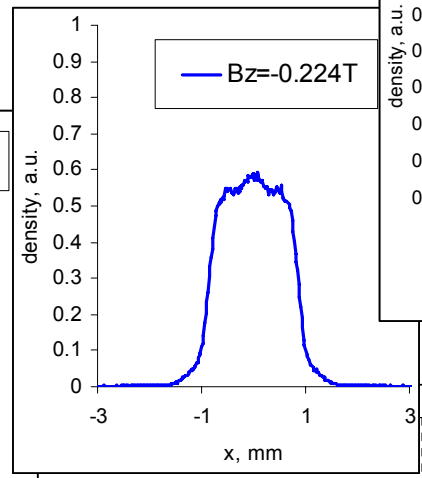
ASTRA simulations. Main solenoid scan.

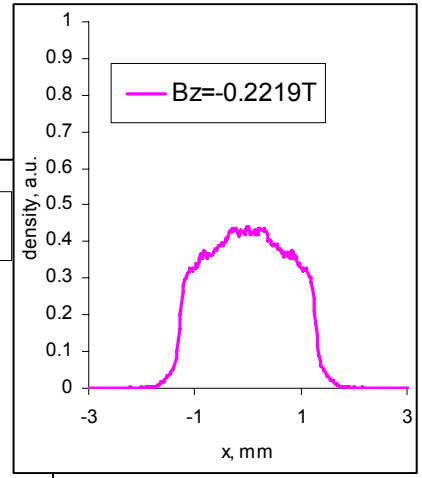
Beam transverse profiles at EMSY

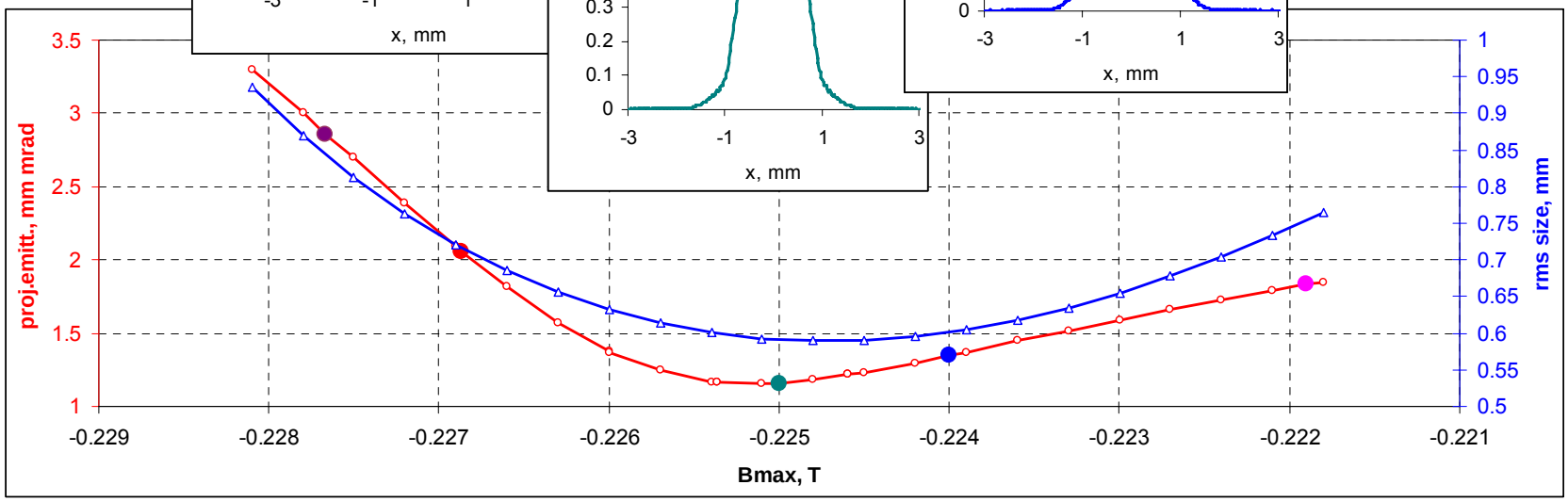








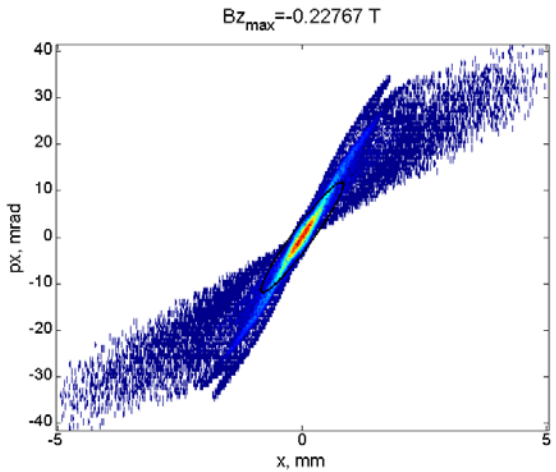


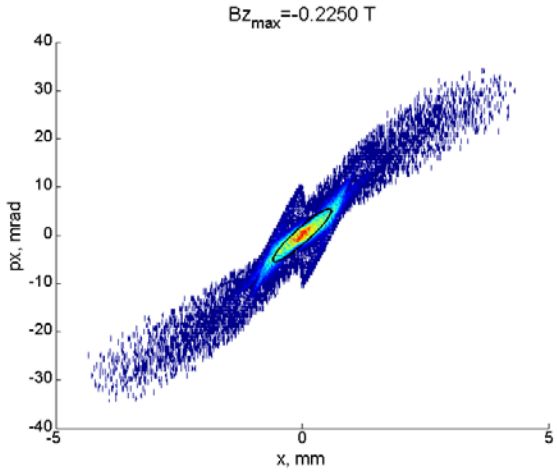


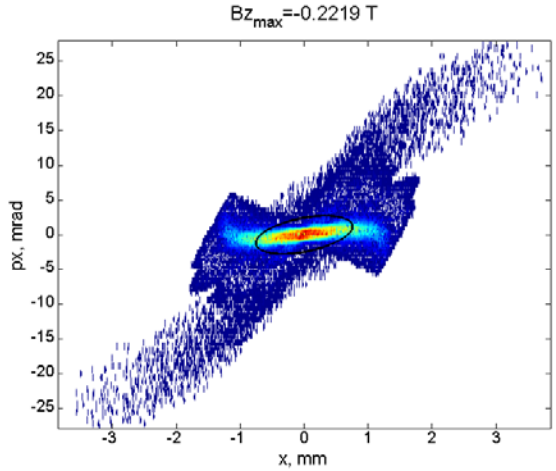
Imain

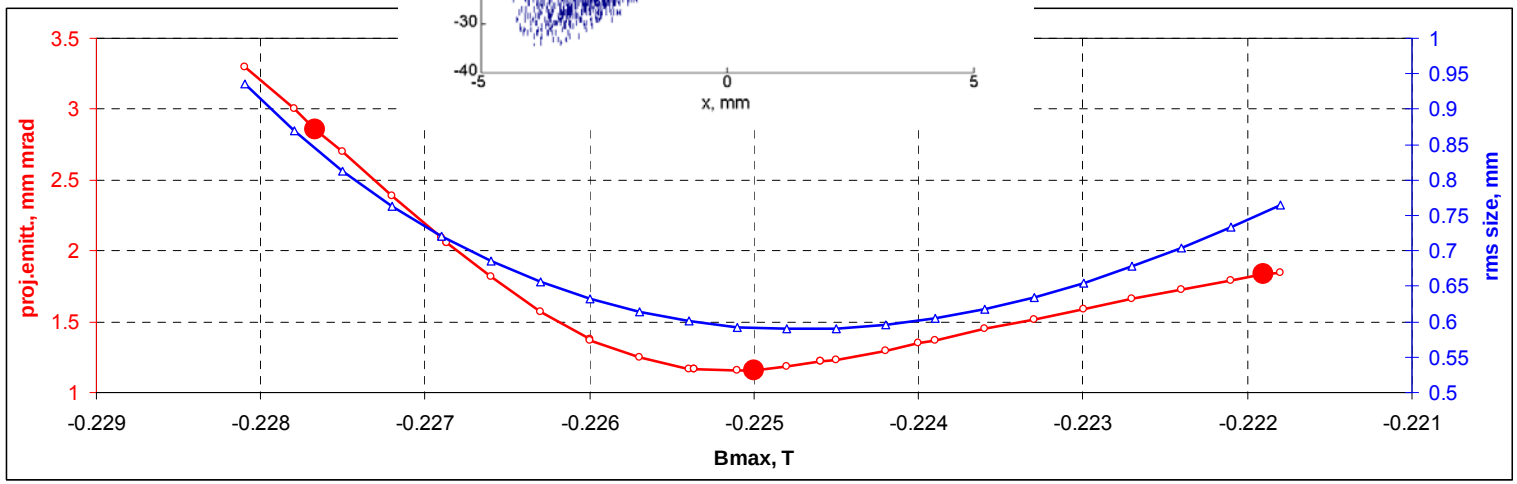
ASTRA simulations. Main solenoid scan.

Beam phase space (x,px)



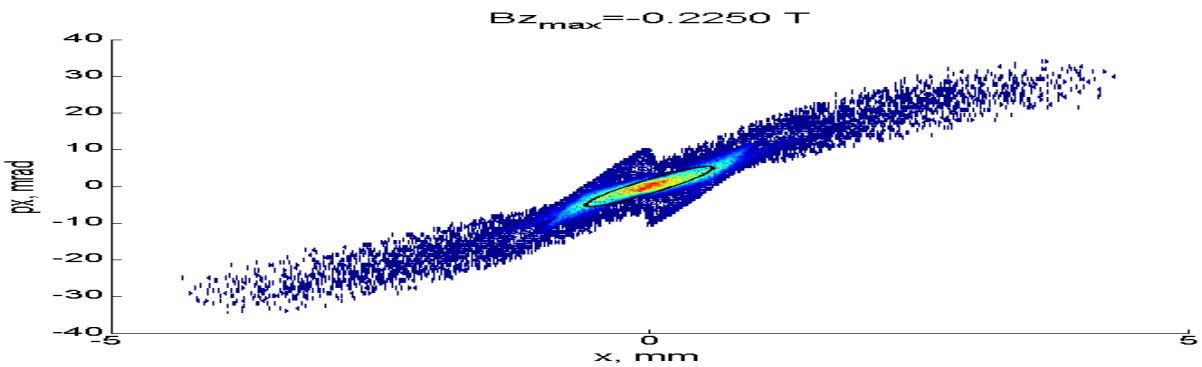






Imain

Single slit scan technique. Main parameters

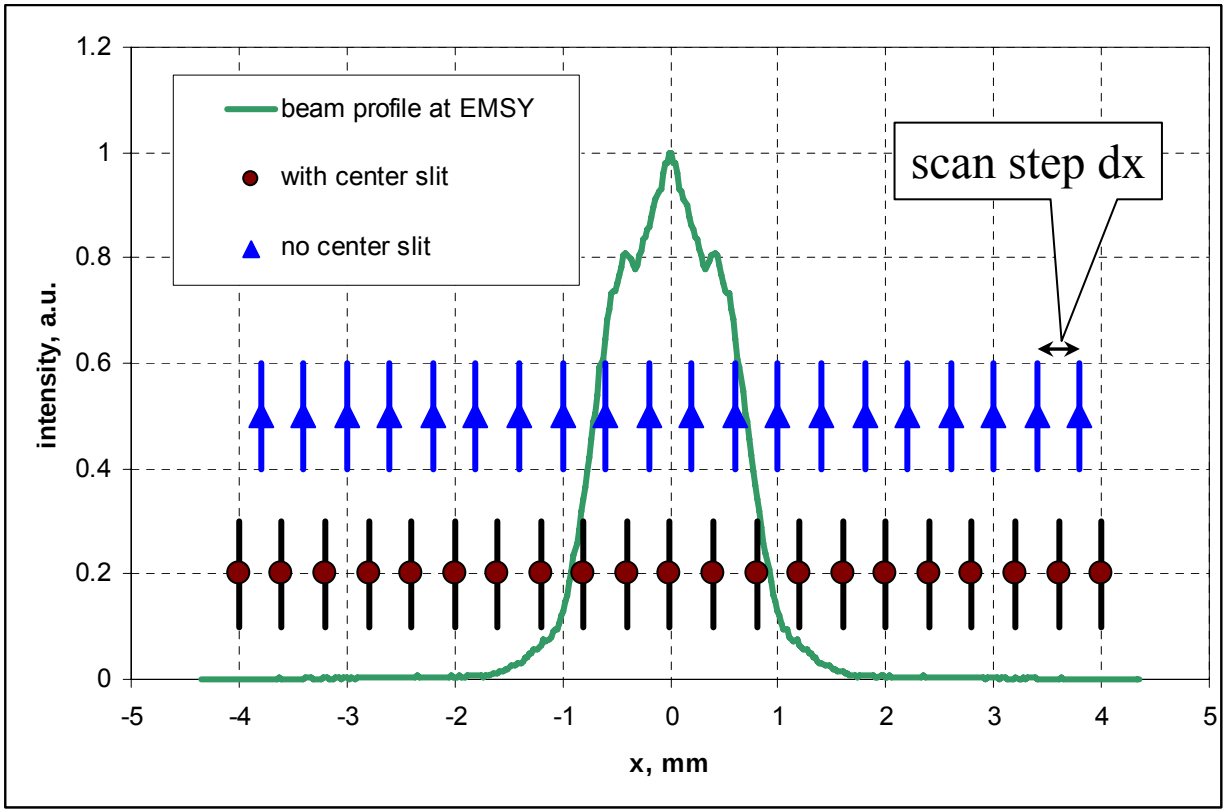


Slit opening =10(50) um:

-S2N ratio

-finite slit opening and thickness impact

-alignment issues



Main parameters for the scan:

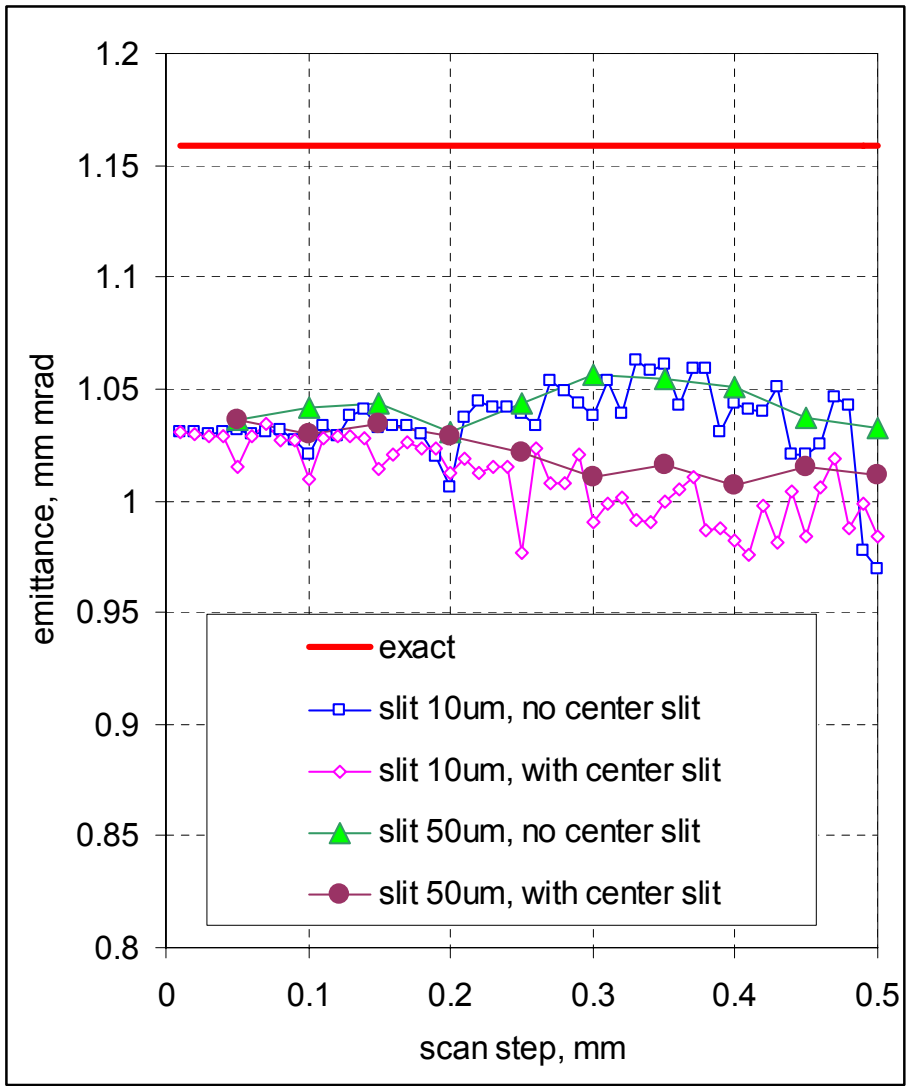
- **Scan step** dx (phase space pattern)
- **Intensity threshold** for scan (start/end for the scan)*
- With/without **center slit** (convergent by dx→0)

Simulated measured emittance vs. scan step

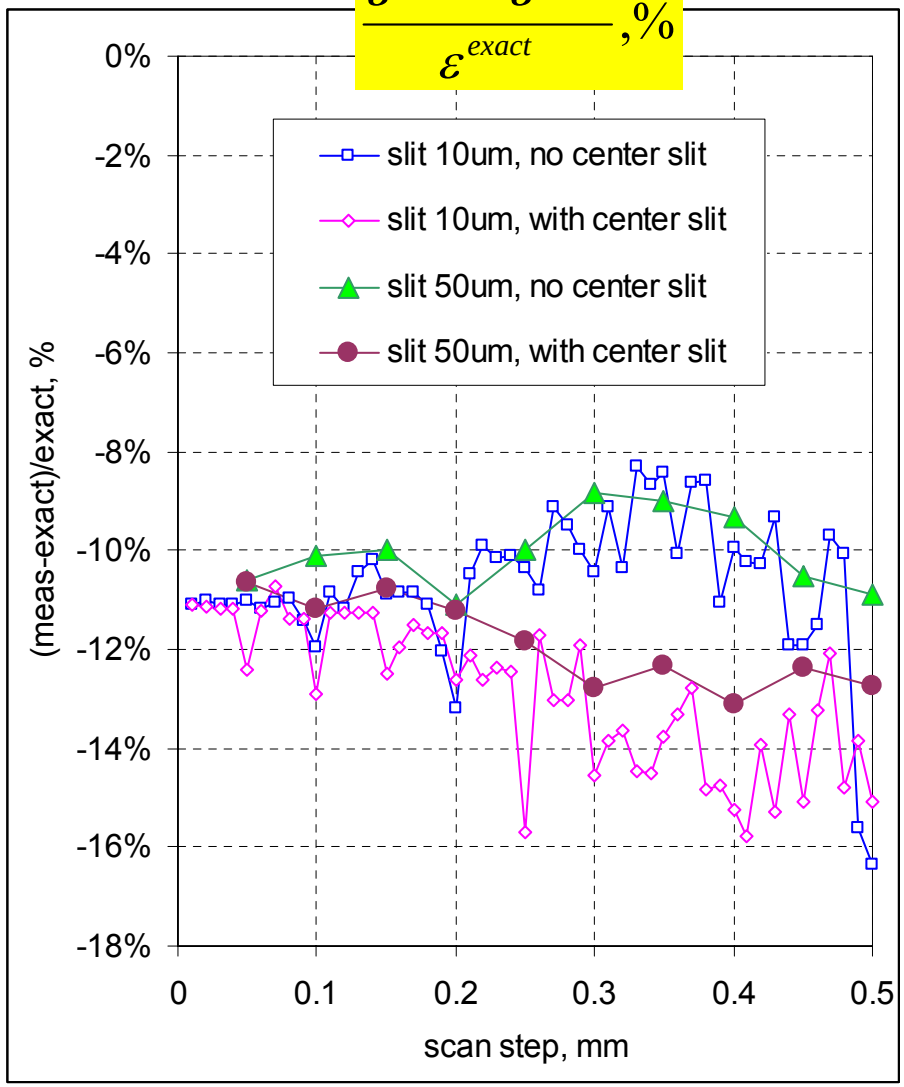
$$\varepsilon_{meas\,0} = \beta\gamma \cdot \sigma_X \cdot \sigma_{X'}$$

$$\sigma_{X'} = \frac{1}{L}\sqrt{\sum_{n=1}^{Nsl} w_n \cdot \left(\sigma_{X',n}^{BL}\right)^2 \Big/ \sum_{n=1}^{Nsl} w_n}$$

~best point Bzmax=-0.2250T

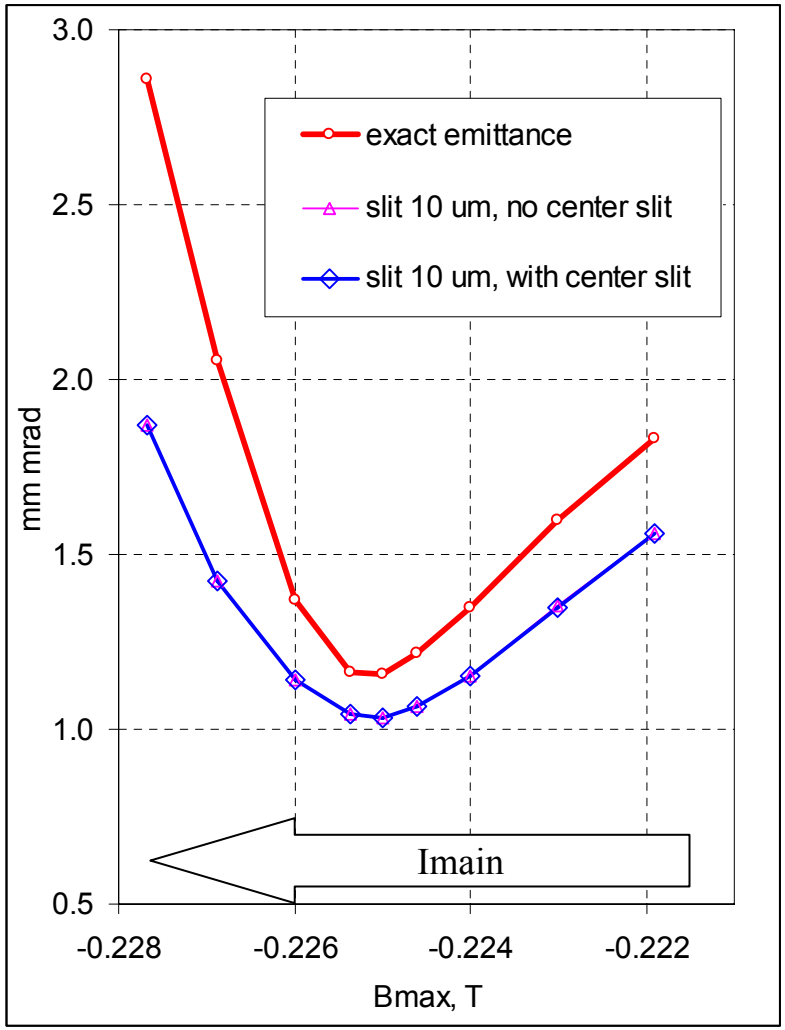


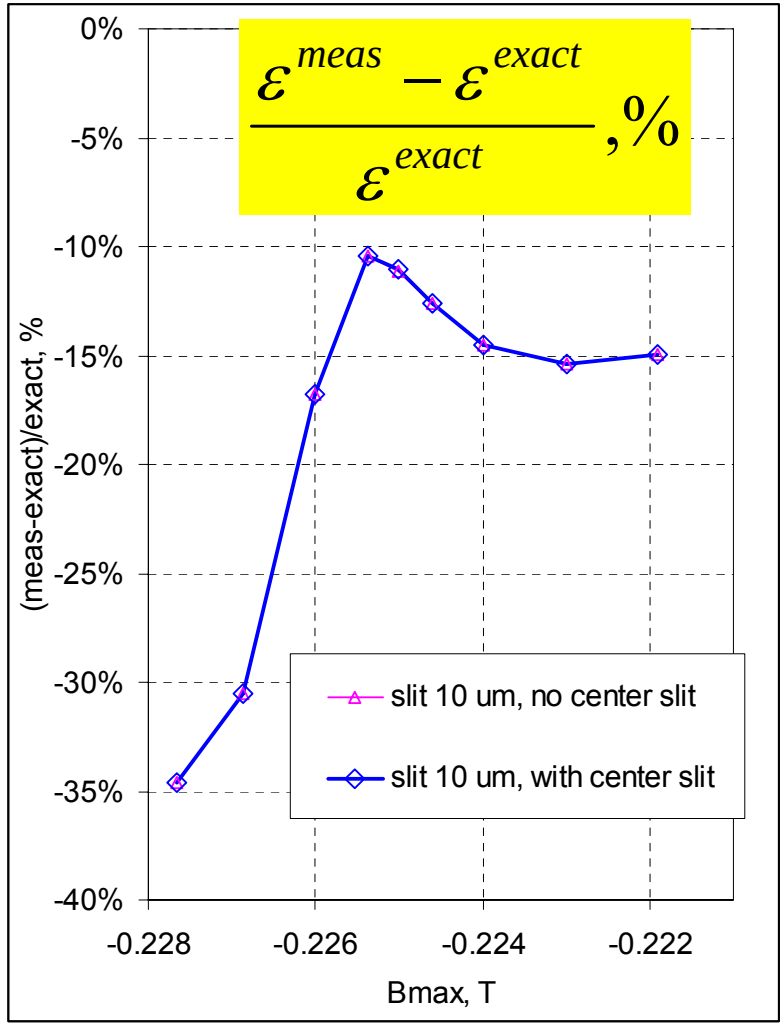
$$\frac{\varepsilon^{meas} - \varepsilon^{exact}}{\varepsilon^{exact}}, \%$$



Simulated measured emittance vs. main solenoid peak field

Main solenoid scan (step size=slit opening=10um)

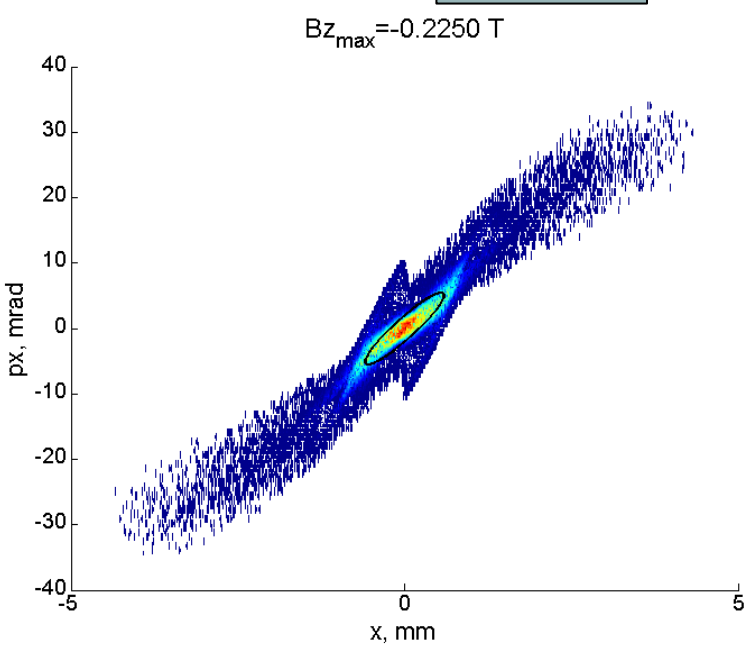


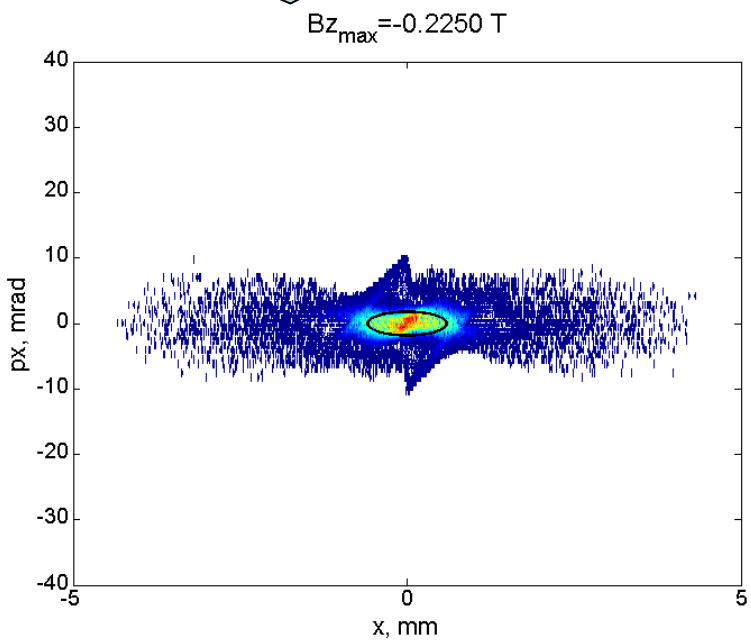


$$\left(\varepsilon^{meas} - \varepsilon^{exact}\right) / \varepsilon^{exact} \approx -10\%!$$

Transverse phase space. Removing correlations

$$\sigma_{X'} = \frac{1}{L}\sqrt{\sum_{n=1}^{Nsl} w_n \cdot \left(\sigma_{X',n}^{BL}\right)^2 \Big/ \sum_{n=1}^{Nsl} w_n}$$



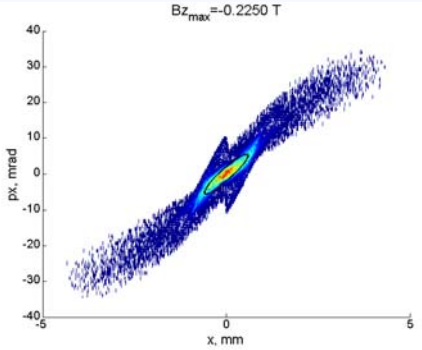


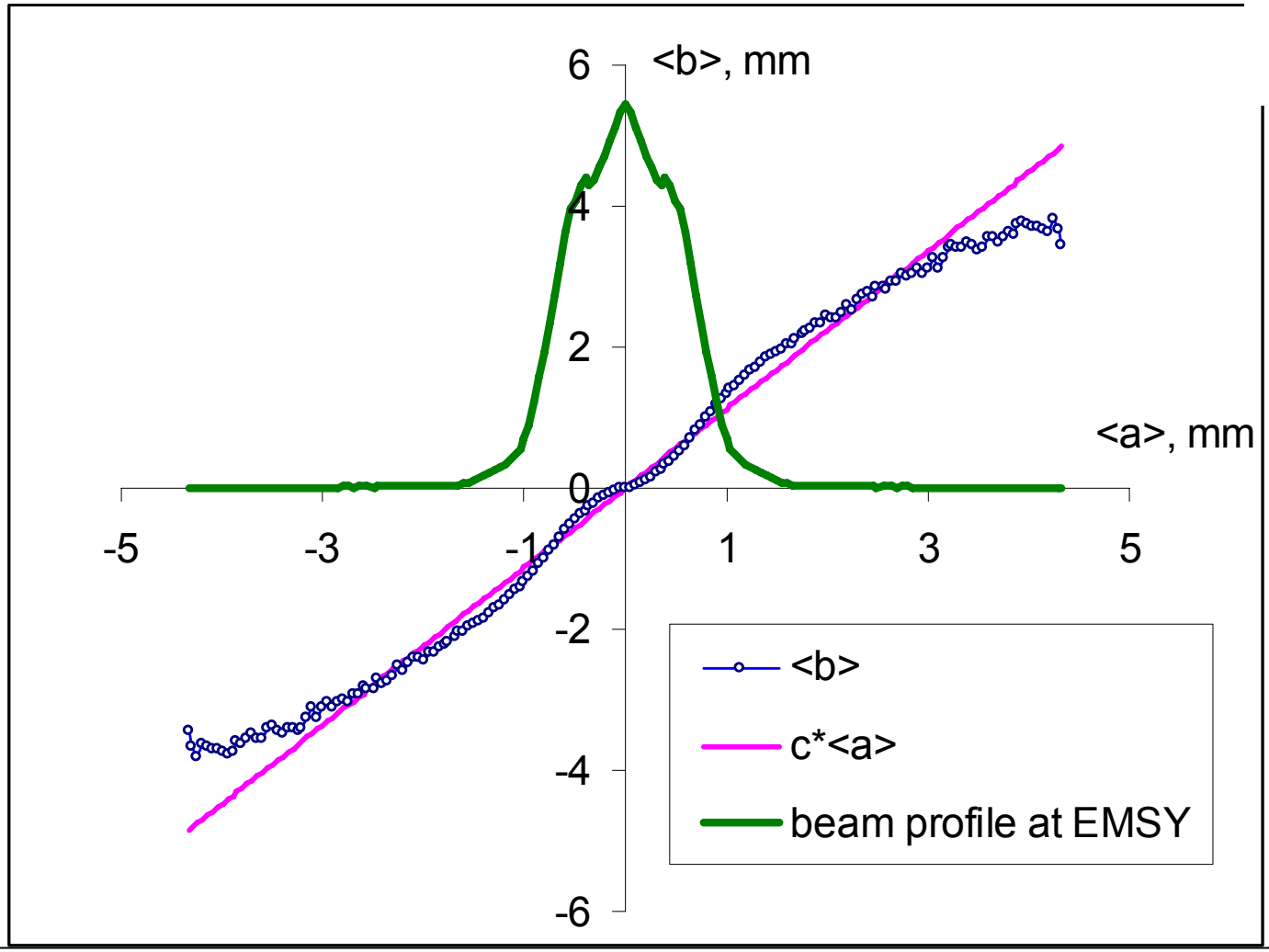
ε=1.16 mm mrad

ε=1.03 mm mrad

Transverse phase space “skeleton”

$$b = x + \frac{px}{pz} \cdot L \Rightarrow \text{coordinate at the beamlet screen}$$



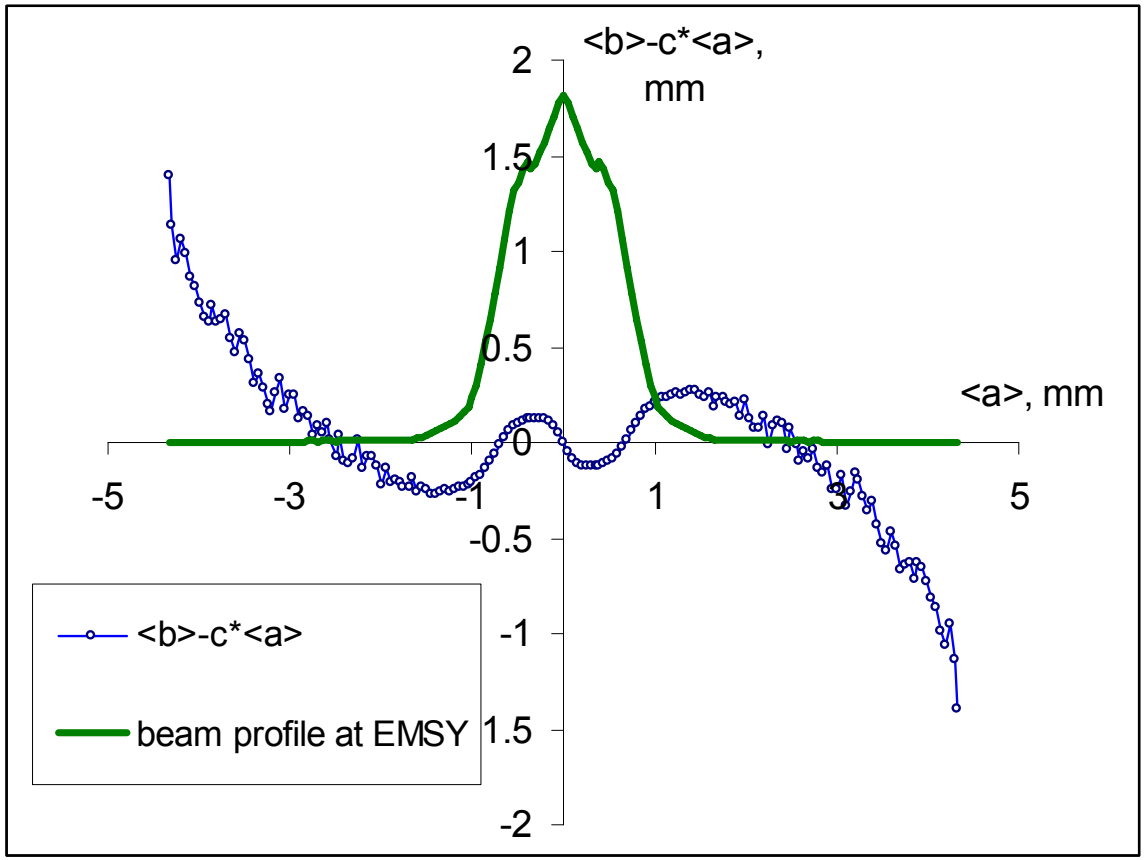


$$a = x$$

$$c = \frac{\sum_s w_s \cdot \bar{a}_s \cdot \bar{b}_s}{\sum_s w_s \cdot \bar{a}_s^2}$$

Transverse phase space “skeleton”. Correction term

$$\varepsilon_{meas}^2 = \varepsilon_{meas0}^2 + \left(\frac{pz0}{L}\right)^2 \left[\sigma_x^2 \cdot \sum_s w_s \cdot \bar{b}_s^2 - \left(\sum_s w_s \cdot \bar{a}_s \cdot \bar{b}_s\right)^2\right]$$



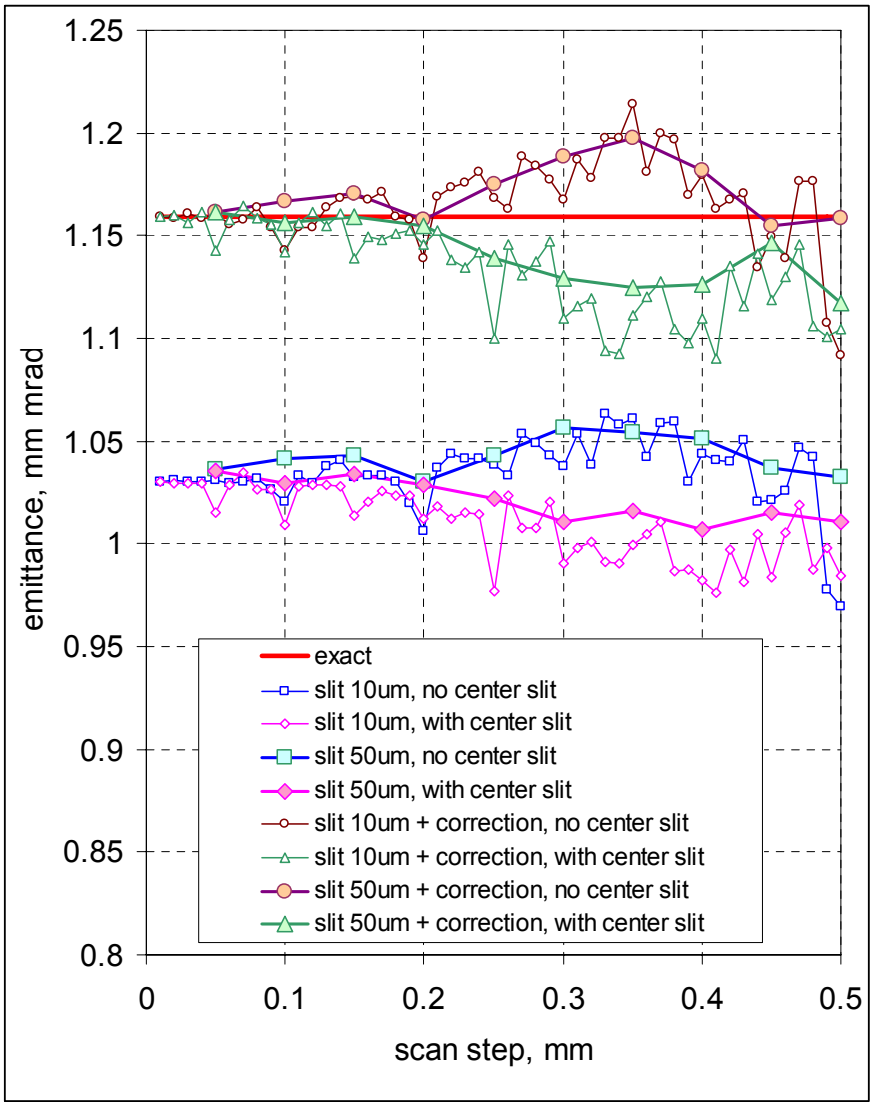
$$\sigma_x^2 \cdot \sum_s w_s \cdot \bar{b}_s^2 - \left(\sum_s w_s \cdot \bar{a}_s \cdot \bar{b}_s\right)^2$$

$$\Downarrow$$

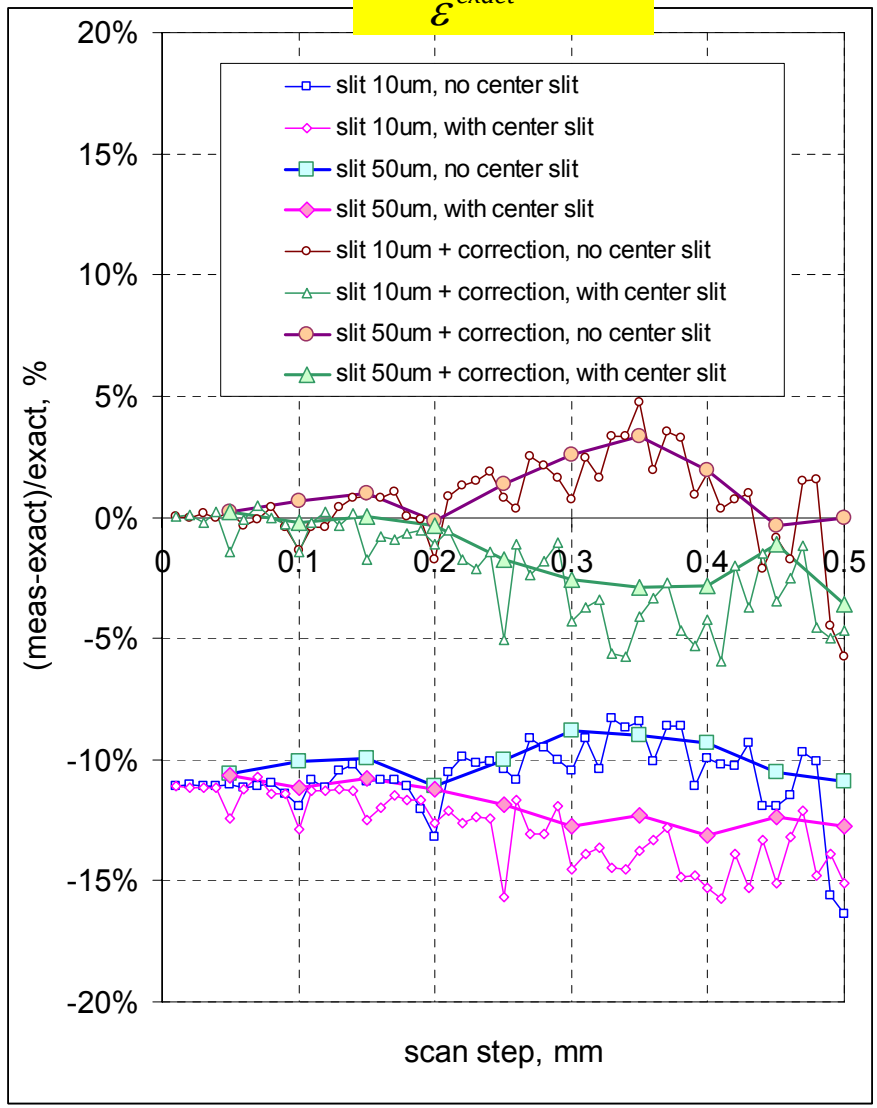
$$\sigma_x^2 \cdot \sum_s w_s \cdot \left(\bar{b}_s - c \cdot \bar{a}_s\right)^2$$

$$c = \frac{\sum_s w_s \cdot \bar{a}_s \cdot \bar{b}_s}{\sum_s w_s \cdot \bar{a}_s^2}$$

Simulated measured emittance vs. scan step with correction

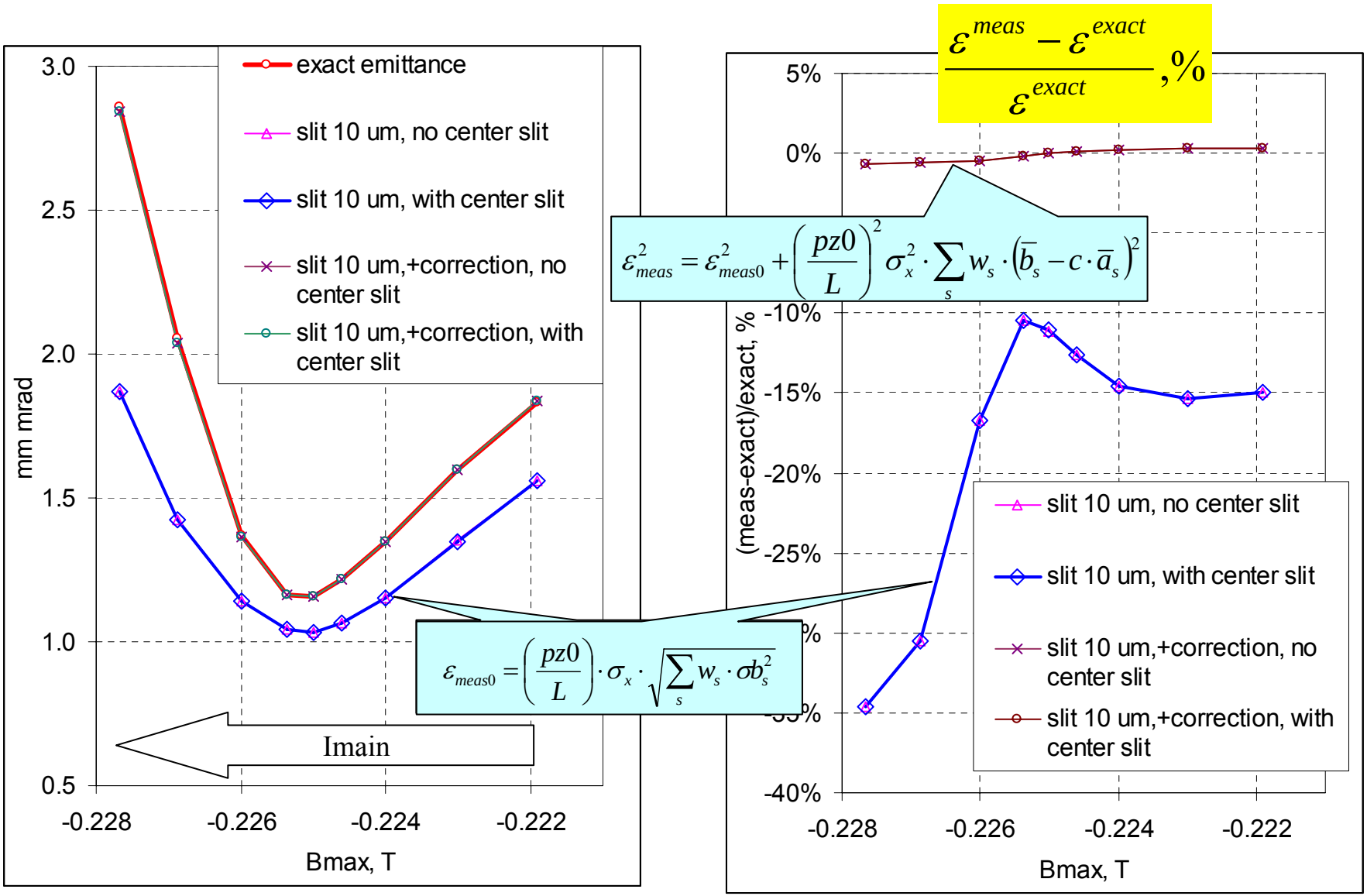


$$\frac{\varepsilon^{meas} - \varepsilon^{exact}}{\varepsilon^{exact}}, \%$$



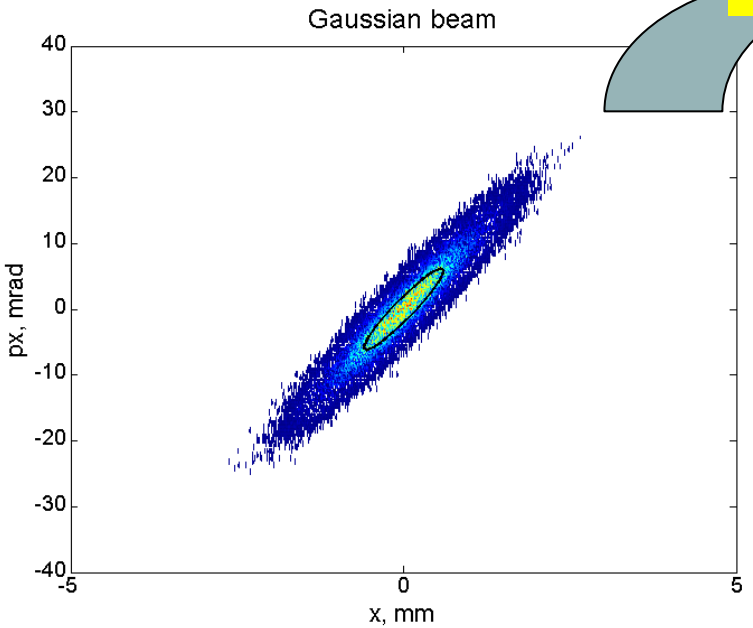
Simulated measured emittance vs. main solenoid peak field with correction

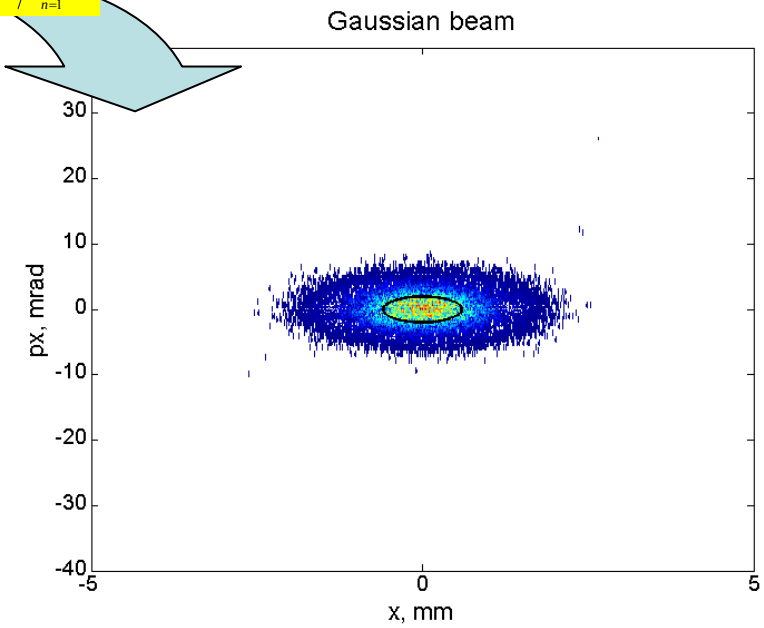
Main solenoid scan (step size=slit opening=10um)

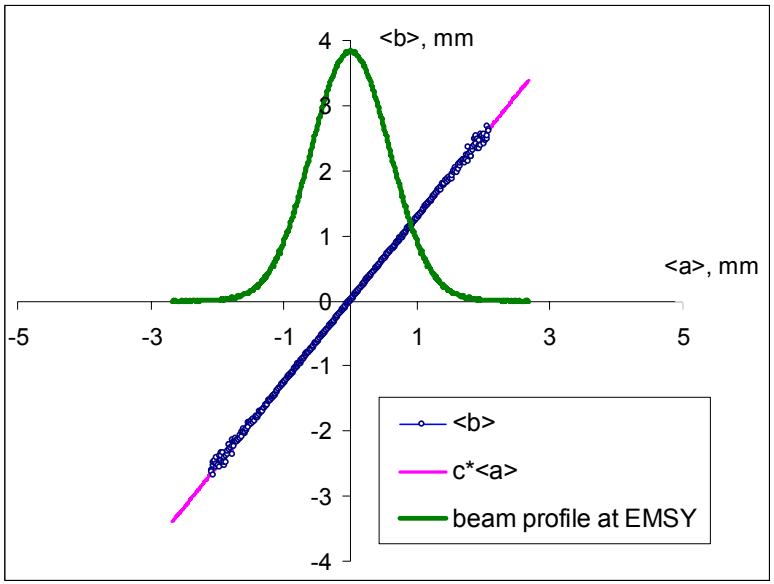


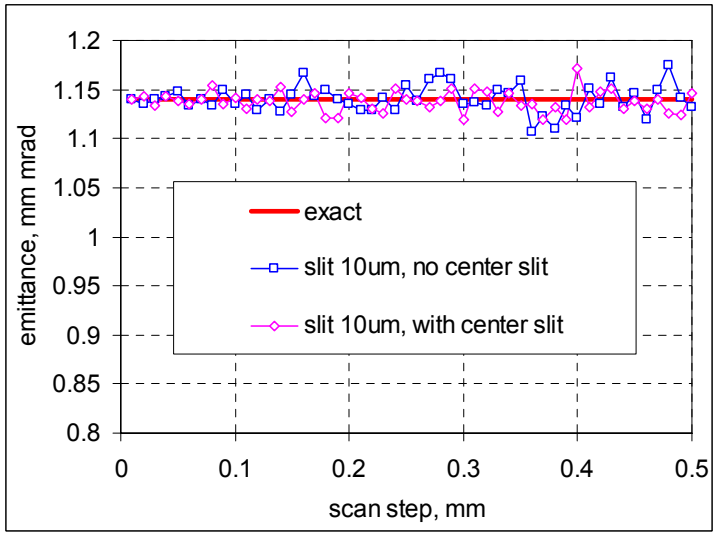
Transverse phase space. Gaussian distribution

$$\sigma_{X'} = \frac{1}{L}\sqrt{\sum_{n=1}^{Nsl} w_n \cdot \left(\sigma_{X',n}^{BL}\right)^2 \Big/ \sum_{n=1}^{Nsl} w_n}$$







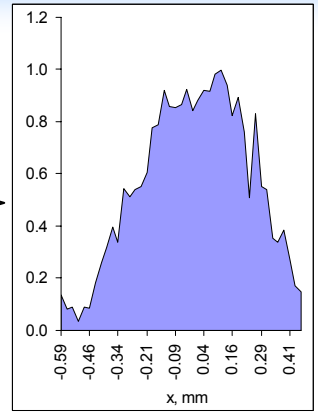


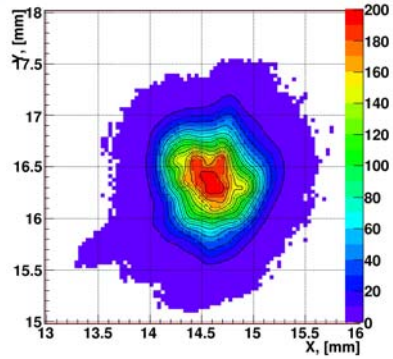
~1%

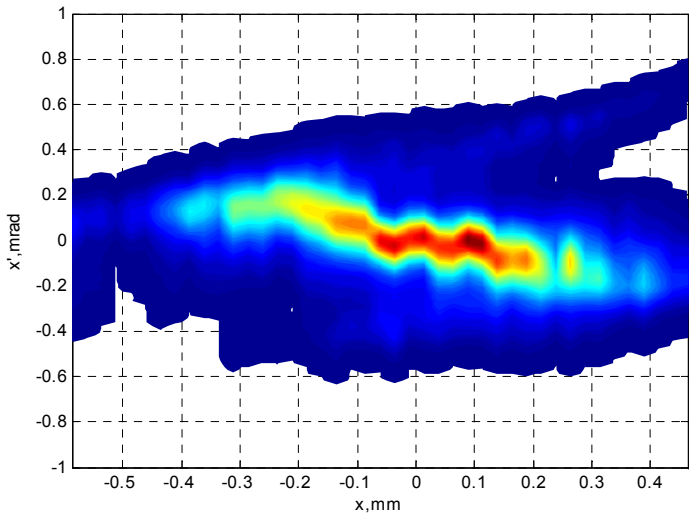
Experimental data: detailed slit scan (17.08.07N)

- dx=25um
- 10um slit opening
- intensity threshold?

projection







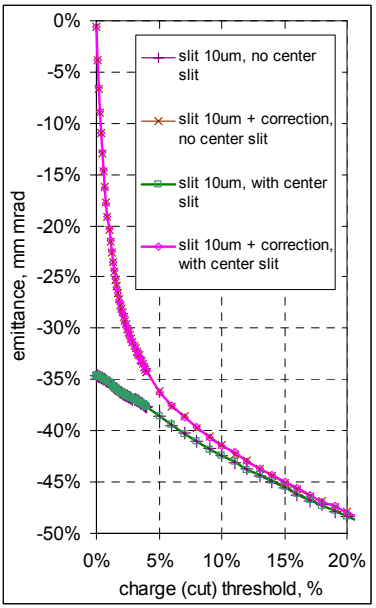
$$\varepsilon_{meas0} = \left(\frac{pz0}{L}\right) \cdot \sigma_x \cdot \sqrt{\sum_s w_s \cdot \sigma b_s^2}$$

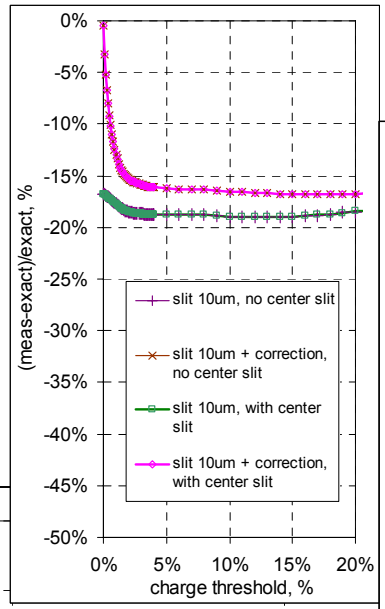
$$\varepsilon_{meas}^2 = \varepsilon_{meas0}^2 + \left(\frac{pz0}{L}\right)^2 \sigma_x^2 \cdot \sum_s w_s \cdot \left(\bar{b}_s - c \cdot \bar{a}_s\right)^2$$

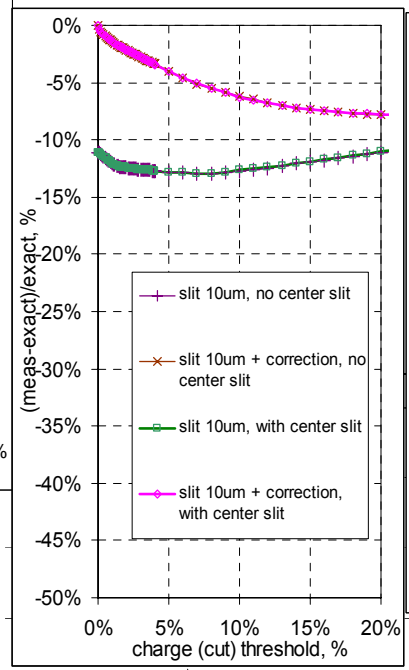
$\sigma_x \rightarrow$	obtained from the beamlet sum of pixels, σ_x=0.226mm	obtained from the whole beam measurement at EMSY, σ_x=0.270mm
Direct from 2D phase space	1.08 mm mrad	1.29 mm mrad (scaled with 0.270/0.226)
Standard formula ε_{meas0}	1.05 mm mrad	**1.26 mm mrad**
+correction ε_{meas}	1.08 mm mrad	**1.29 mm mrad**

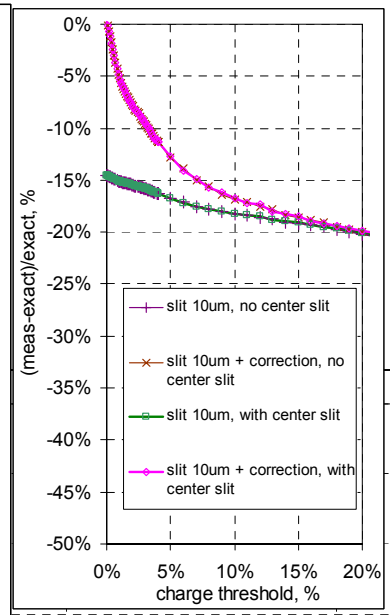
Intensity threshold influence for various solenoid peak fields

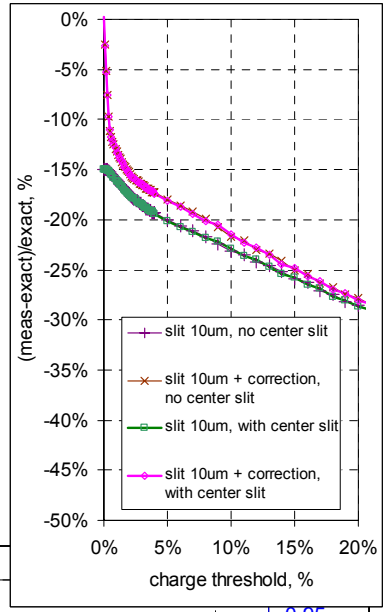
Main solenoid scan (step size=slit opening=10um)

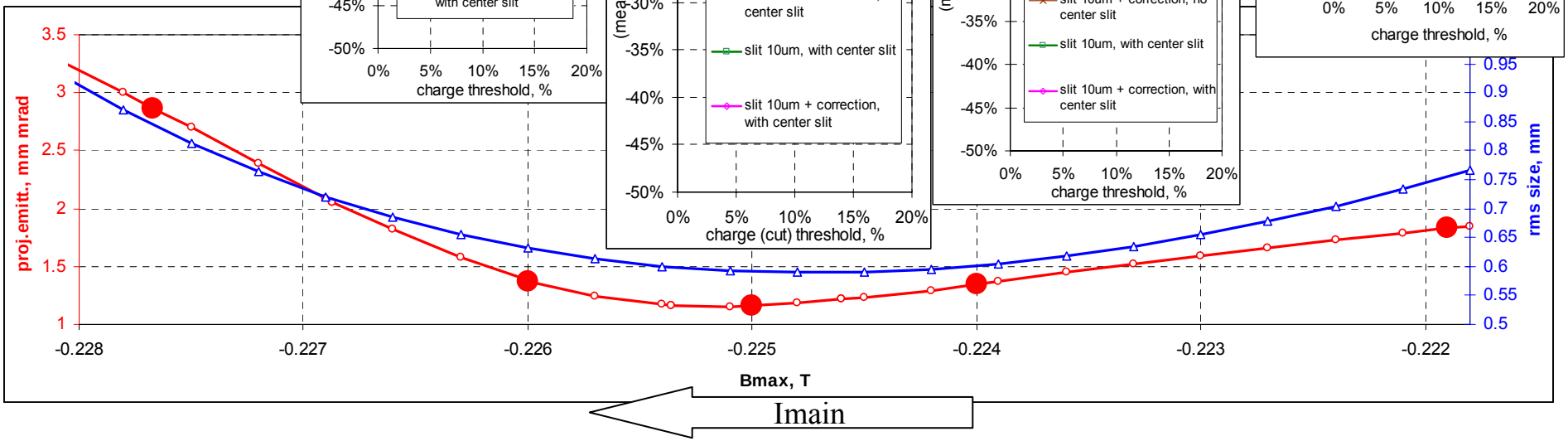




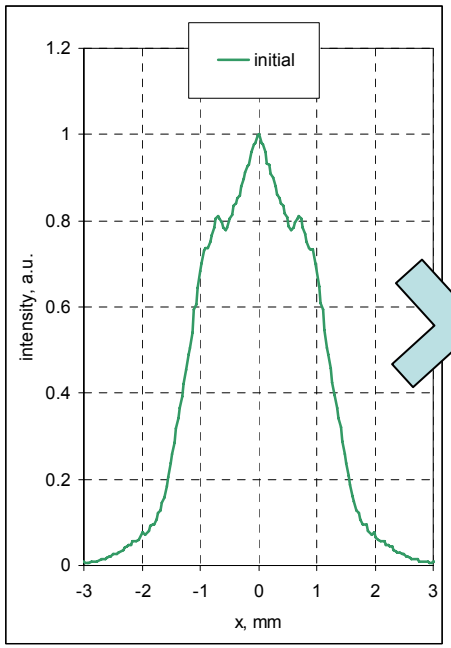




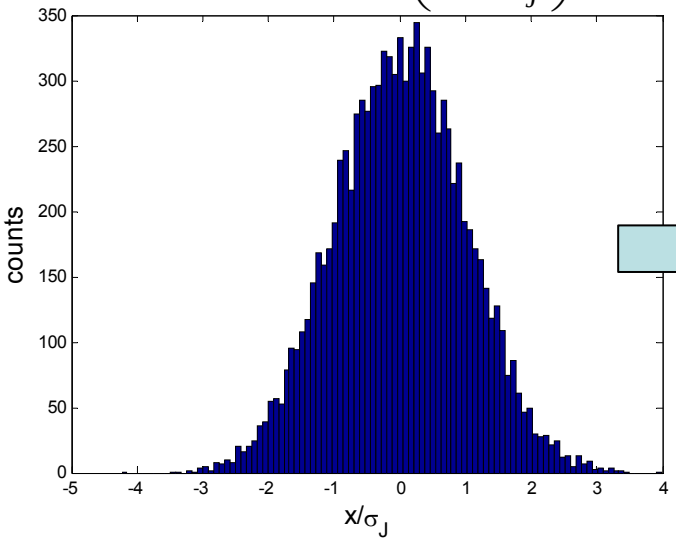


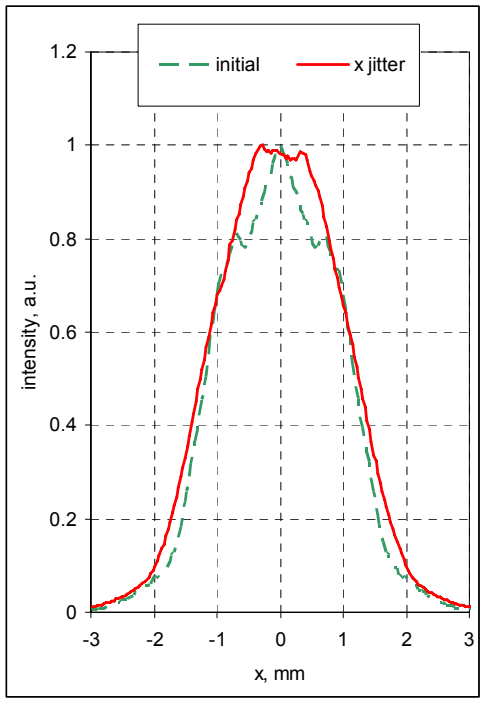


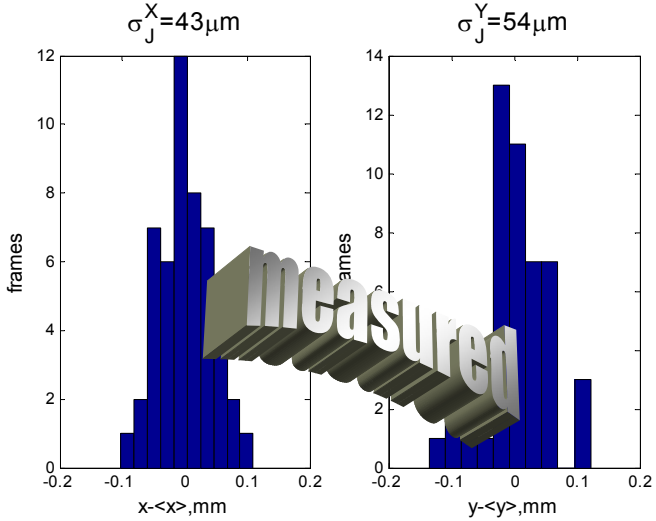
Position jitter of electron beam

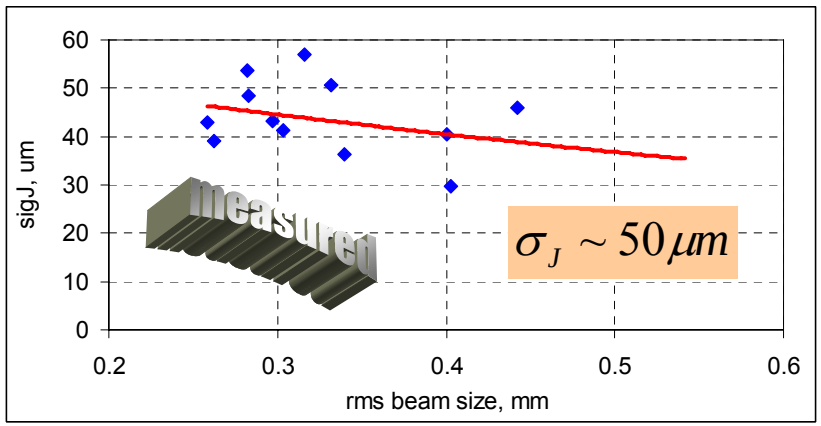


$$P(x_n) \propto \exp\left(-\frac{x_n^2}{2\sigma_J^2}\right)$$









Position jitter of electron beam

$G(x-x_n,\sigma_x)$ - beam profile

$$P(x_n) \propto \exp\left(-\frac{x_n^2}{2\sigma_J^2}\right)$$

$N \propto$ number of pulses

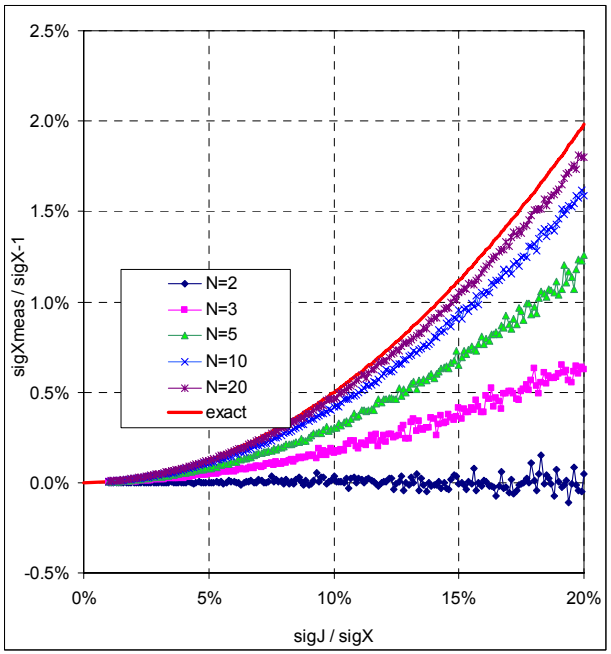
$$\sigma_x^{meas} = \sqrt{\sigma_x^2 + \frac{1}{N}\sum_{n=1}^{N} x_n^2 - \frac{1}{N^2}\left(\sum_{n=1}^{N} x_n\right)^2}$$

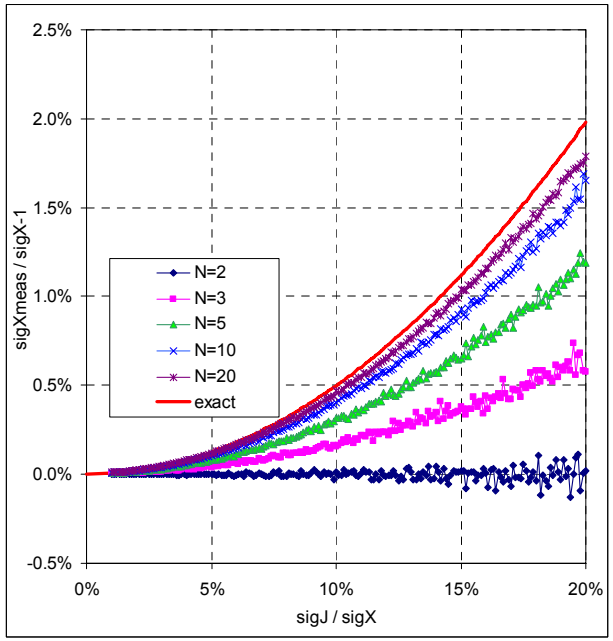
$N \to \infty$

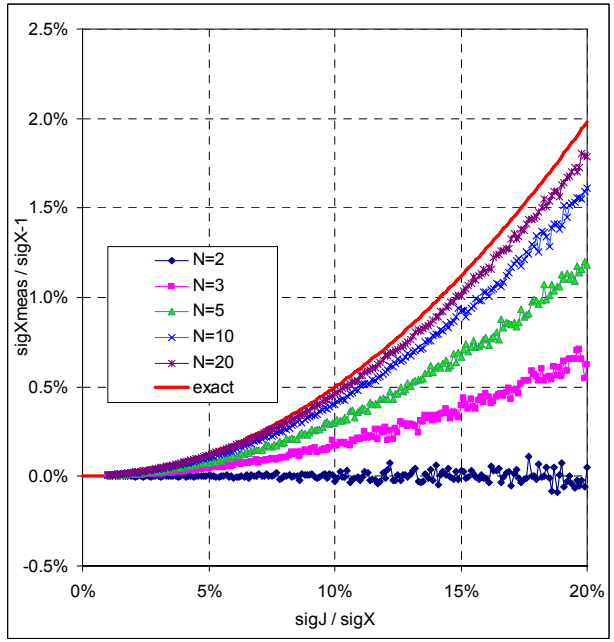
$$\sigma_x^{meas,exact} = \sqrt{\sigma_x^2 + \sigma_J^2}$$

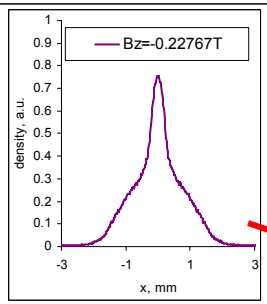
Beam rms size increase due to the position jitter

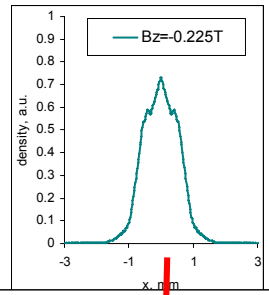
Increase of the **measured** beam rms size vs. rms position jitter σ_J

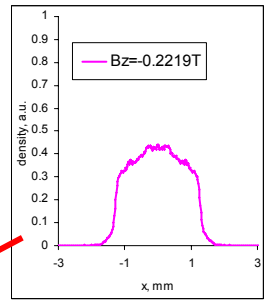


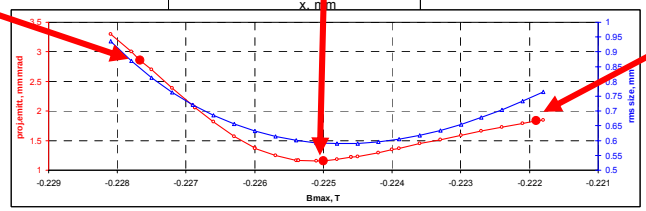












<0.5% @ 10% jitter

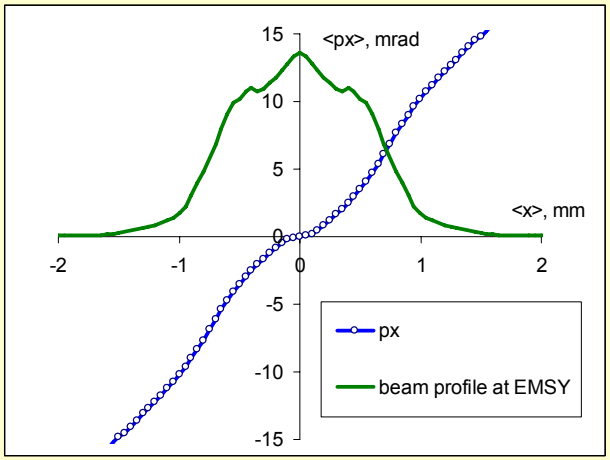
Beam position jitter. Influence onto beamlets

RMS size of the beamlet including beam position jitter at the slit (**linear approximation**):

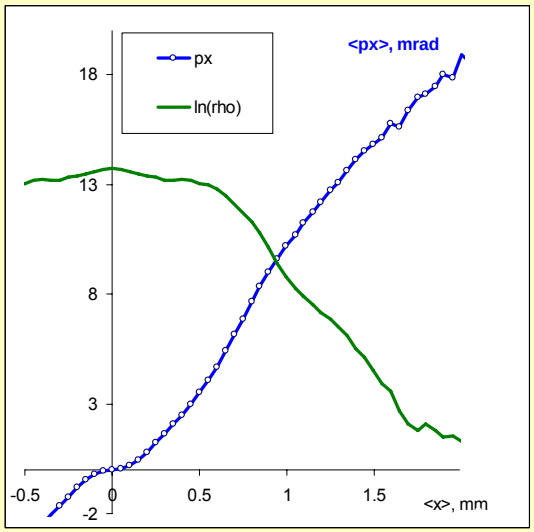
$$\sigma_b^2 = \sigma_{b0}^2 + \sigma_J^2 \cdot \left\{ \alpha^2 \cdot \left[1 - \left(\frac{d \ln \rho}{dx} \right)^2 \sigma_J^2 \right] + \frac{d\sigma_b^2}{dx} \frac{d \ln \rho}{dx} \right\}$$

BL size increase due to the transv.momentum gradient

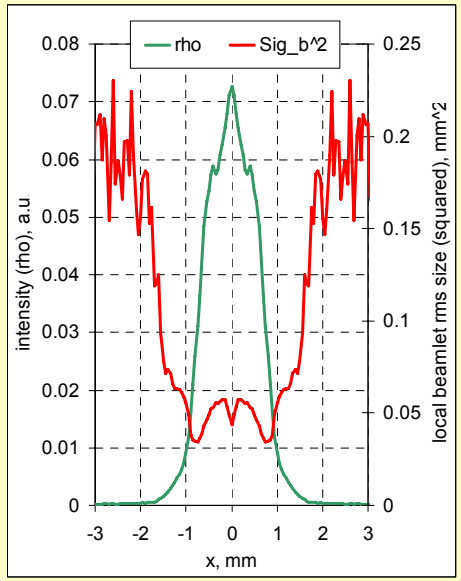
$$\alpha = \frac{L}{p_z} \cdot \frac{dp_x}{dx}$$



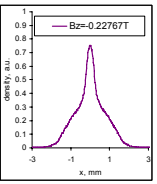
Change of the beamlet center position

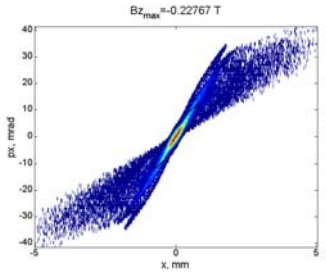


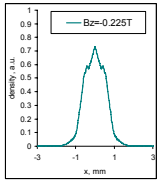
Beamlet size / beam profile gradient

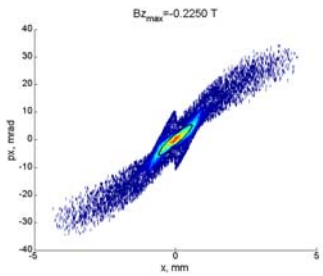


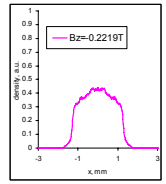
Measured emittance increase due to the **linear** beam position jitter

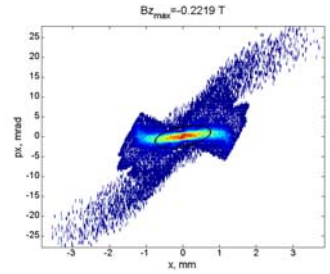


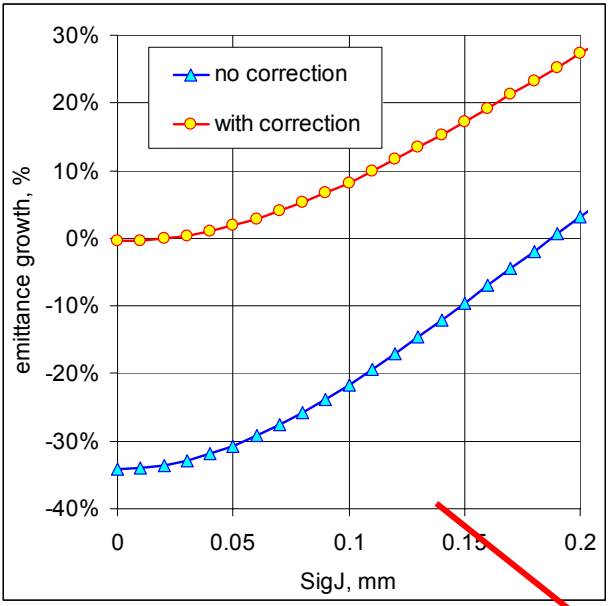


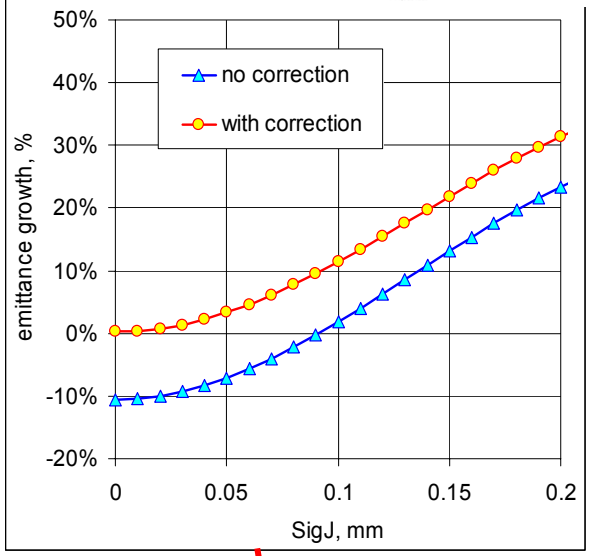


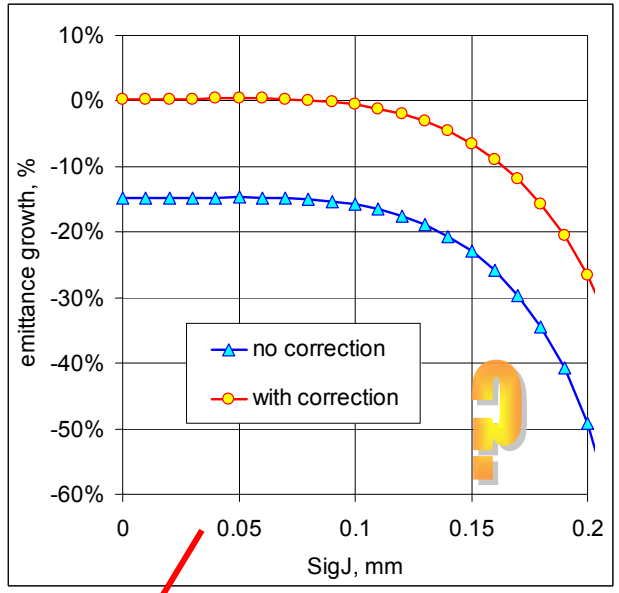


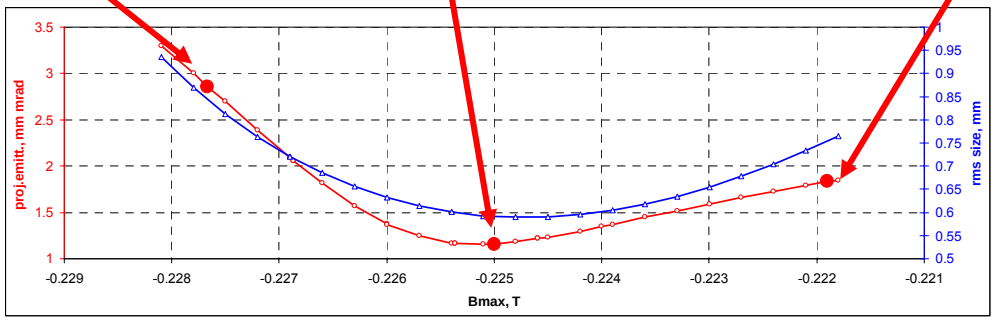






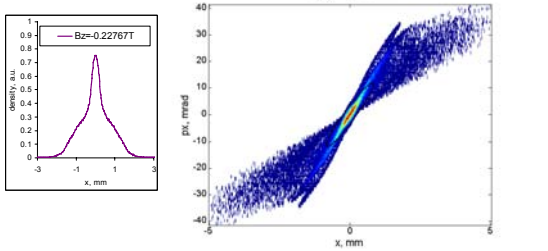


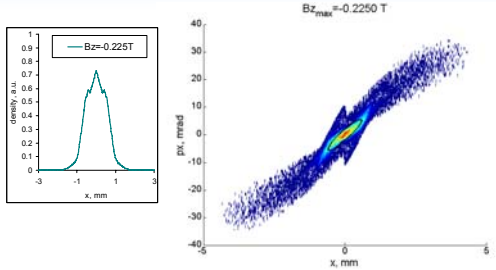


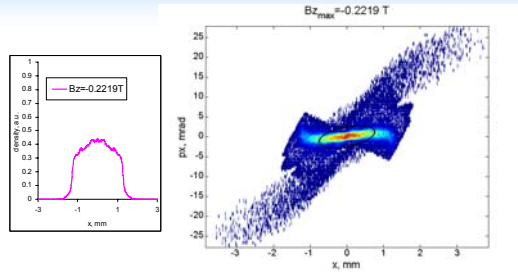


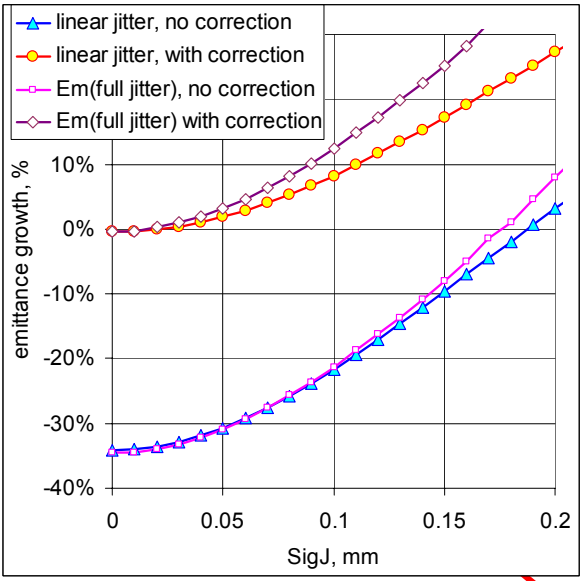
Scan step=10um

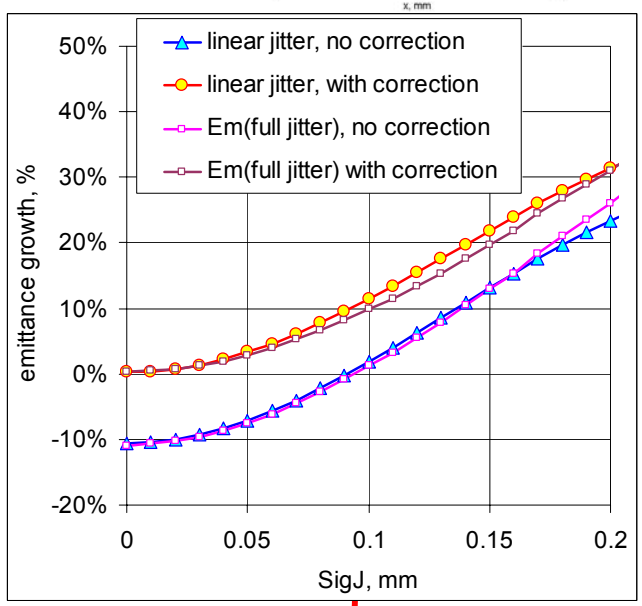
Measured emittance increase due to the beam position jitter

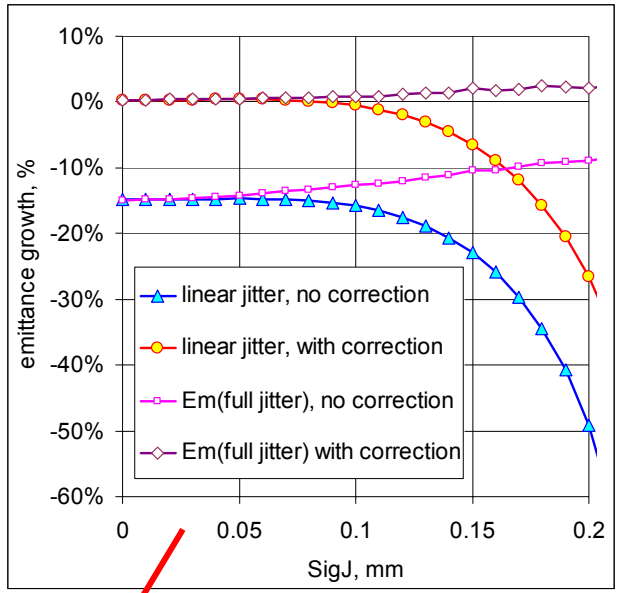


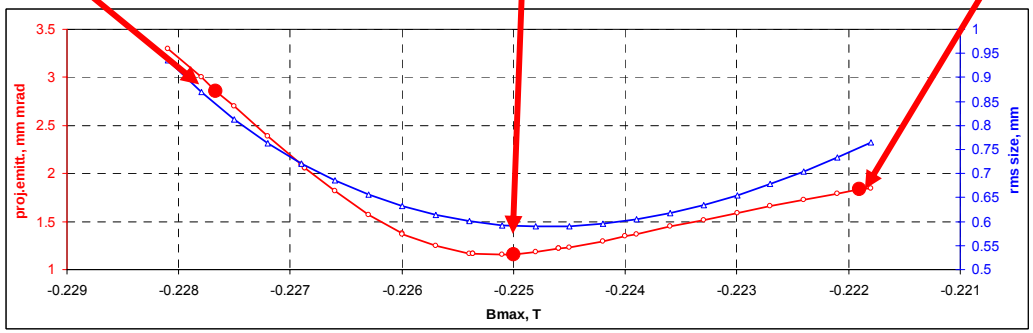








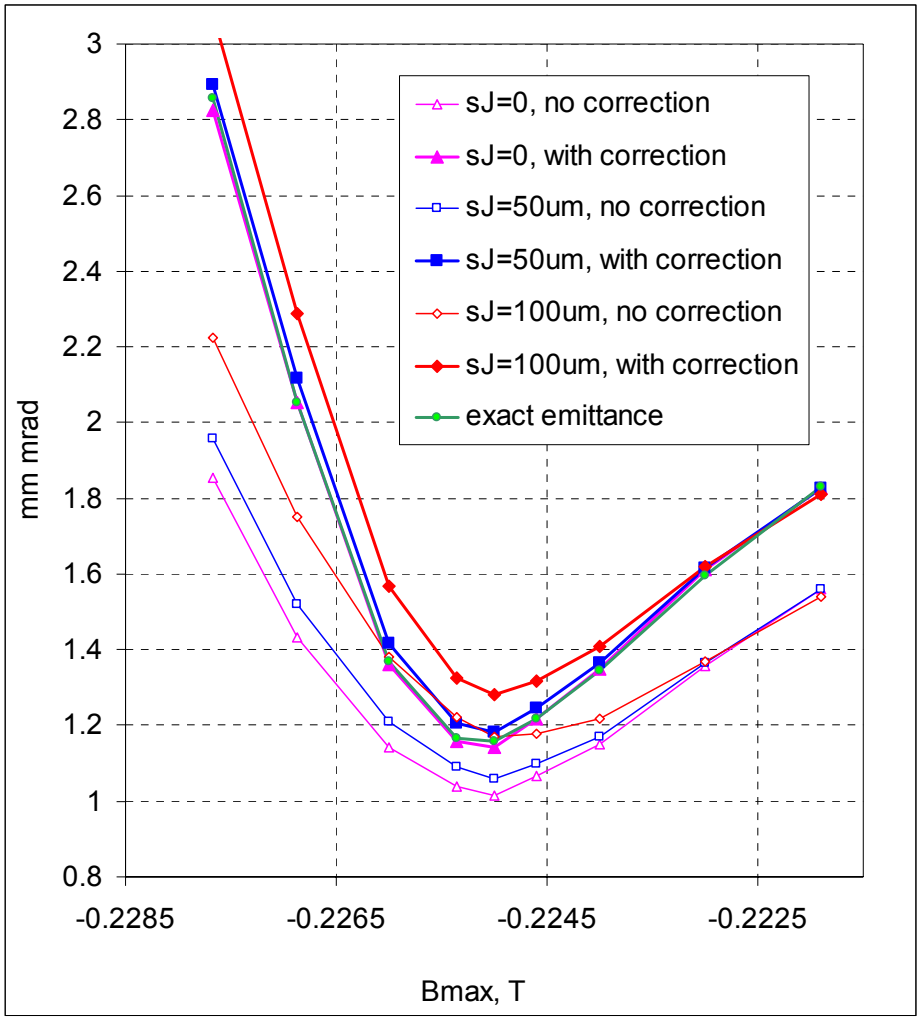


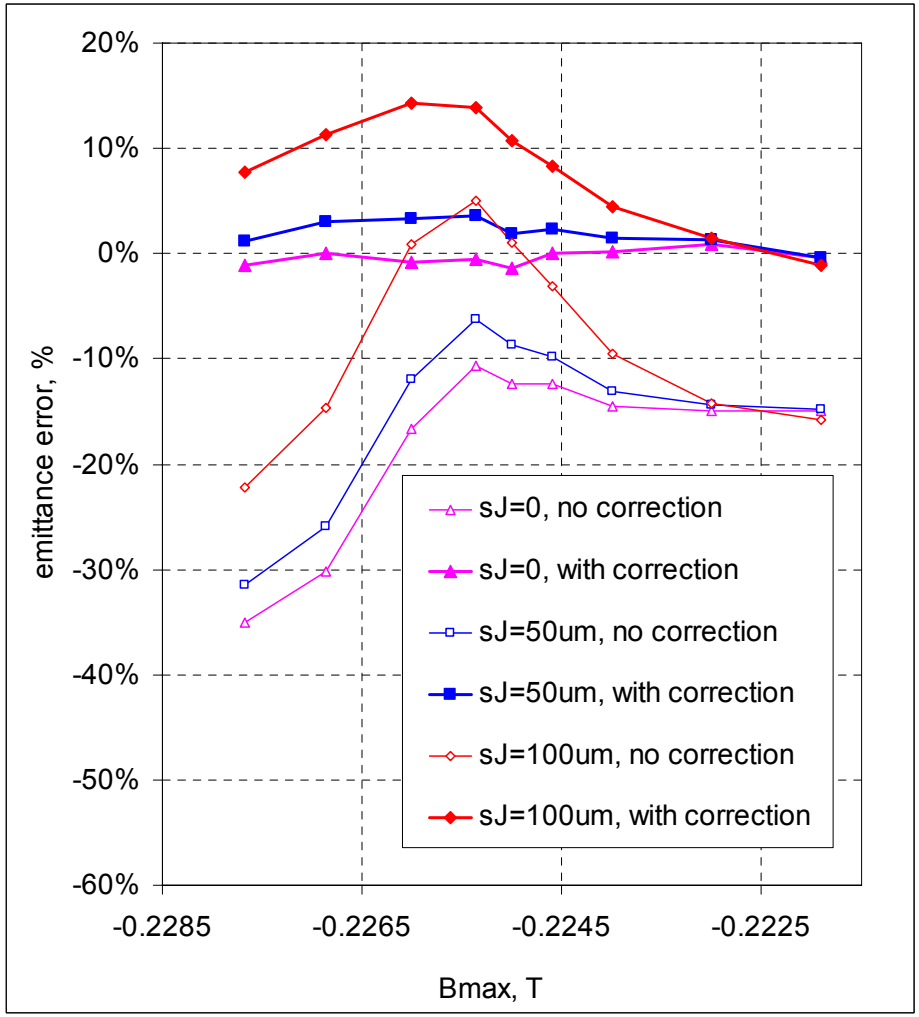


Scan step=10um

Slit scan X Beam position jitter=Measured emittance

Scan step=100um, charge cut threshold=0%





Conclusions

- Factors affecting slit scan measurements:

Factor	Effect on measured emittance	Solution/remark
Phase space nonlinearity	-10..-30%	correction term experimentally ~-2..-3%
Scan step dx	~1% if dx<200um	dx~100um
Beam position jitter	+5% @ 50 um rms jitter	• improve stability • ?measurement with synchronized BPM?

- Combined factors (dx=100um X 50um position jitter) resulted in 0…+4% measured emittance overestimation

- There is an influence of the intensity (charge) cut (not discussed here) resulting in the emittance underestimation (i,e. -5..-30% for 5% charge cut)