Beam Diagnostics of the SRF Photoinjector at HZDR

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on behalf of

the ELBE and the Rossendorf SRF Gun Crew

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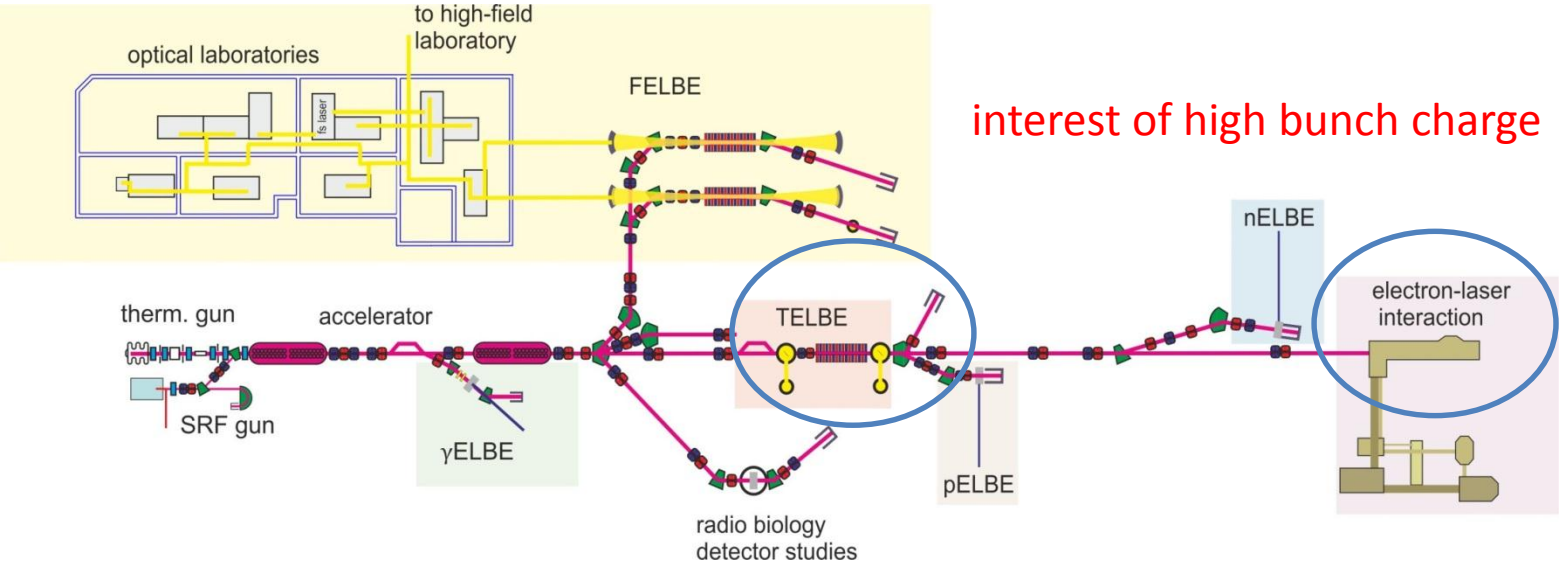
Outline

- **Introduction** — ELBE, SRF gun
- **Scheme** — what and how to diagnose
- **Results** — measured, simulated, error
- **Outlook** — what is also possible?

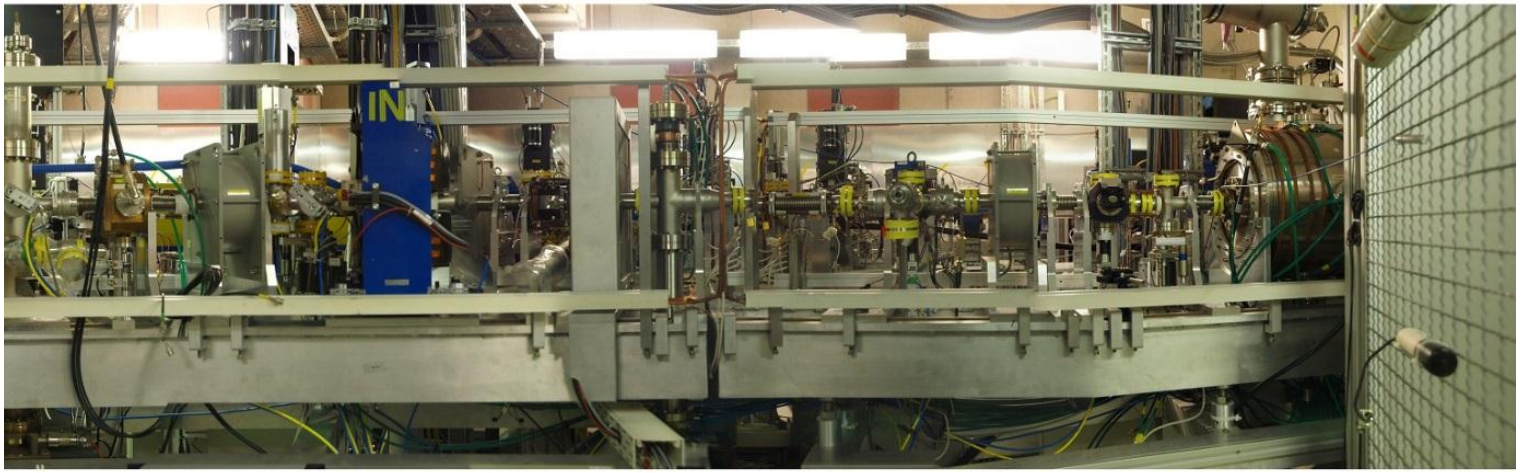
- **Intro.**
- **Scheme**
- **Results**
- **Outlook**

ELBE accelerator



interest of high bunch charge

1mA, 40MeV CW electron accelerator



- Intro.
- Scheme
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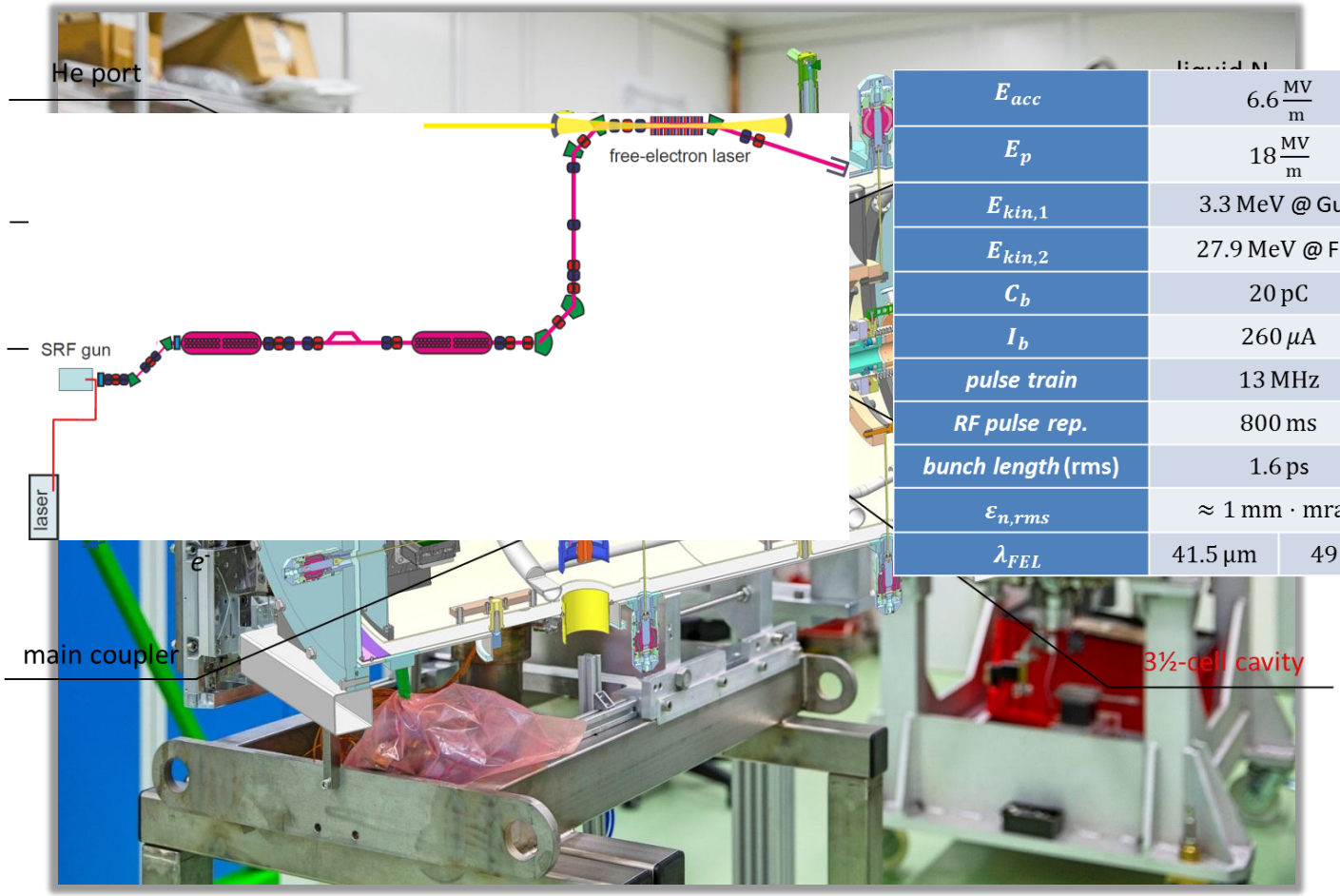
ELBE SRF Gun I & II



E_{acc}	$6.6\,\frac{\mathrm{MV}}{\mathrm{m}}$	
E_p	$18\,\frac{\mathrm{MV}}{\mathrm{m}}$	
$E_{kin,1}$	3.3 MeV @ Gun	
$E_{kin,2}$	27.9 MeV @ FEL	
C_b	20 pC	
I_b	260 μA	
pulse train	13 MHz	
RF pulse rep.	800 ms	
bunch length (rms)	1.6 ps	
$\varepsilon_{n,rms}$	$\approx$ 1 mm · mrad	
λ_{FEL}	41.5 µm	49 µm

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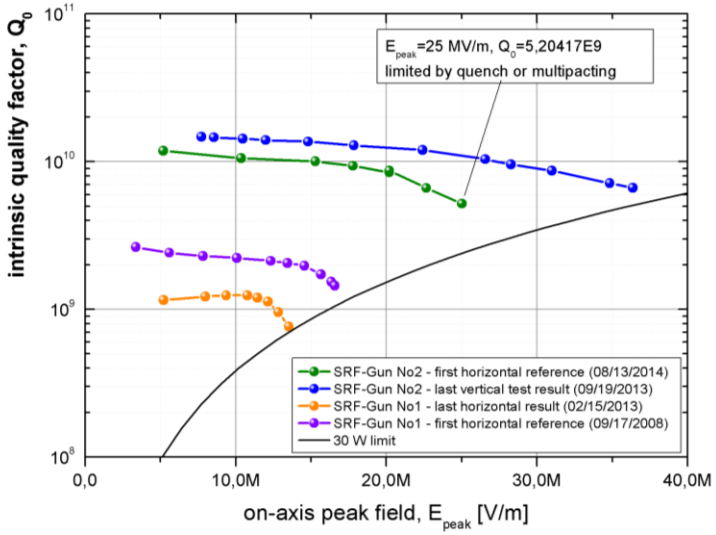
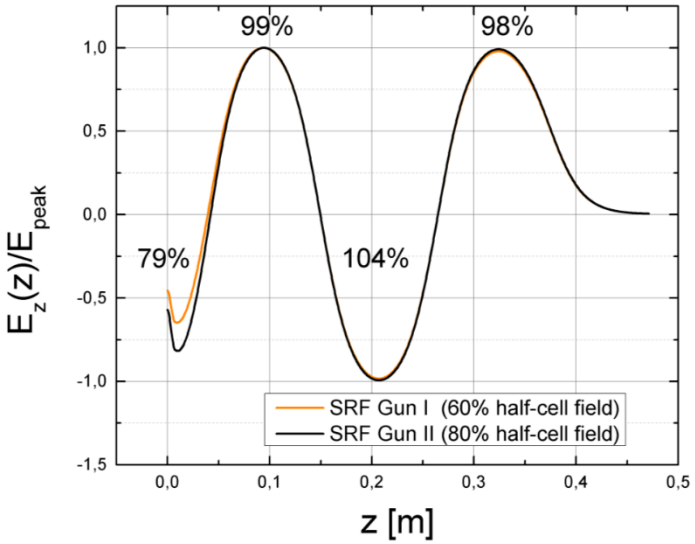
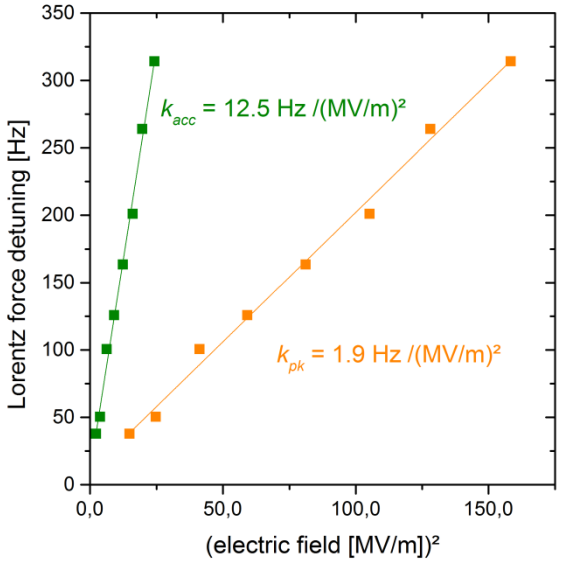
RF performance







comparison with	SRF gun I	TESLA cavity
k_{acc} / Hz/(MV/m)²	5	1
k_{pk} / Hz/(MV/m)²	0.69	0.25

- **Intro.**
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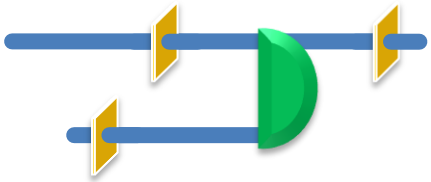
desired / developed diagnostics

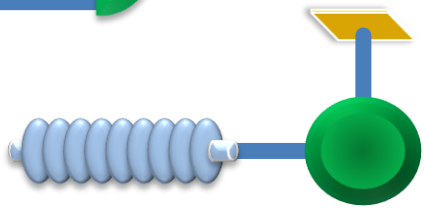
desired: 6D phase space along the beamline, for a single bunch

developed: statistics average parameters, 1D/2D projection at fixed positions, overlapped bunches

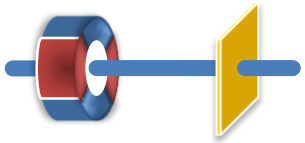
- ✓ energy, energy spread :



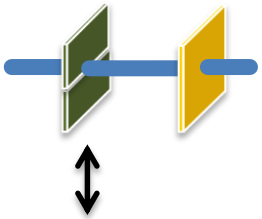
- ✓ longitudinal phase ellipse: phase scan



- ✓ transverse phase ellipse: quadrupole scan



- ✓ transverse phase space: slit scan



transverse phase ellipse — quadrupole scan

$$M_{quad} = \begin{pmatrix} a & b \\ c & d \end{pmatrix},\ M_L = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix},\ M_{total} = \begin{pmatrix} a+cL & b+dL \\ c & d \end{pmatrix}$$

$$\underbrace{\beta_2\varepsilon}_{f} = \underbrace{(a+cL)^2}_{x}\ \underbrace{\beta_1\varepsilon}_{A} \underbrace{-2(a+cL)(b+dL)}_{y}\underbrace{\alpha_1\varepsilon}_{B} + \underbrace{(b+dL)^2}_{z}\ \underbrace{\gamma_1\varepsilon}_{C}$$

"thin lens assumption"

or one parameter (k) fitting

$$f = Ax + By + Cz$$

$$\sigma_{11}(s) = \sigma_{11}(0)\cdot\left[\cos\left(\sqrt{k}\,l\right) - d\sqrt{k}\sin\left(\sqrt{k}\,l\right)\right]^2 + \sigma_{12}(0)\cdot\left[2\left[\cos\left(\sqrt{k}\,l\right) - d\sqrt{k}\sin\left(\sqrt{k}\,l\right)\right]\cdot\left[\frac{1}{\sqrt{k}}\sin\left(\sqrt{k}\,l\right) + d\cos\left(\sqrt{k}\,l\right)\right]\right] + \sigma_{22}(0)\cdot\left[\frac{1}{\sqrt{k}}\sin\left(\sqrt{k}\,l\right) + d\cos\left(\sqrt{k}\,l\right)\right]^2$$

known f,x,y,z, Least squares method to calculate A,B,C

$$Minimize:\ R = \sum\left[\frac{1}{\sigma_{fi}}(f_i - Ax_i - By_i - Cz_i)^2\right],$$

$$\frac{\partial R}{\partial A} = 0,\quad \frac{\partial R}{\partial B} = 0,\quad \frac{\partial R}{\partial C} = 0 \Longrightarrow \begin{pmatrix} A \\ B \\ C \end{pmatrix} = \begin{pmatrix} \sum\frac{f_i x_i}{\sigma_{fi}} \\ \sum\frac{f_i y_i}{\sigma_{fi}} \\ \sum\frac{F_i z_i}{\sigma_{fi}} \end{pmatrix} \begin{pmatrix} \sum\frac{x_i^2}{\sigma_{fi}} & \sum\frac{x_i y_i}{\sigma_{fi}} & \sum\frac{x_i z_i}{\sigma_{fi}} \\ \sum\frac{y_i x_i}{\sigma_{fi}} & \sum\frac{y_i^2}{\sigma_{fi}} & \sum\frac{y_i y z_i}{\sigma_{fi}} \\ \sum\frac{z_i x_i}{\sigma_{fi}} & \sum\frac{}{\sigma_{fi}} & \sum\frac{z_i^2}{\sigma_{fi}} \end{pmatrix}^{-1} \Longrightarrow \begin{matrix} \alpha_1 \\ \beta_1 \\ \gamma_1 \\ \varepsilon \end{matrix}$$

whatever

- Intro.
- Scheme
- Results
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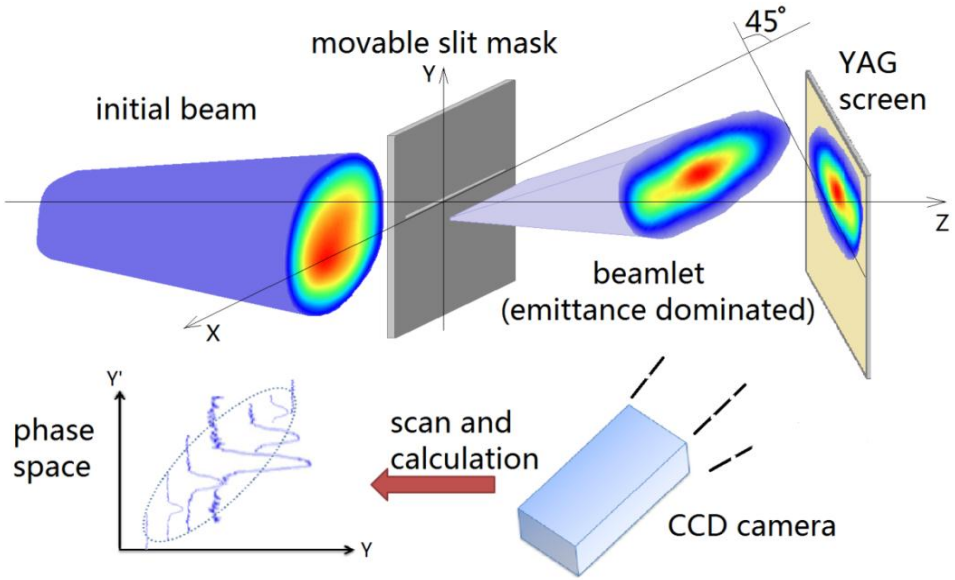
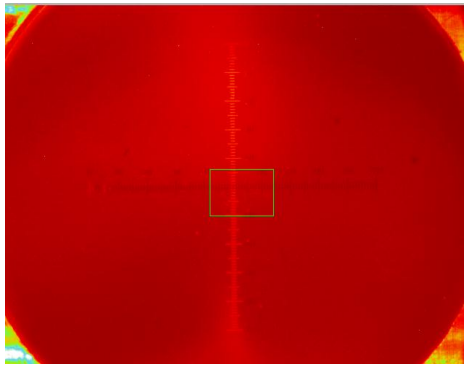
- σ_{fi} determines the weight of images
- $M_{quad} = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ is not limited to quadrupole matrix

transverse phase space — slit scan





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

Compared to quadrupole scan

- detailed phase space
- no “constant emittance assumption”
- relay more on beam stability

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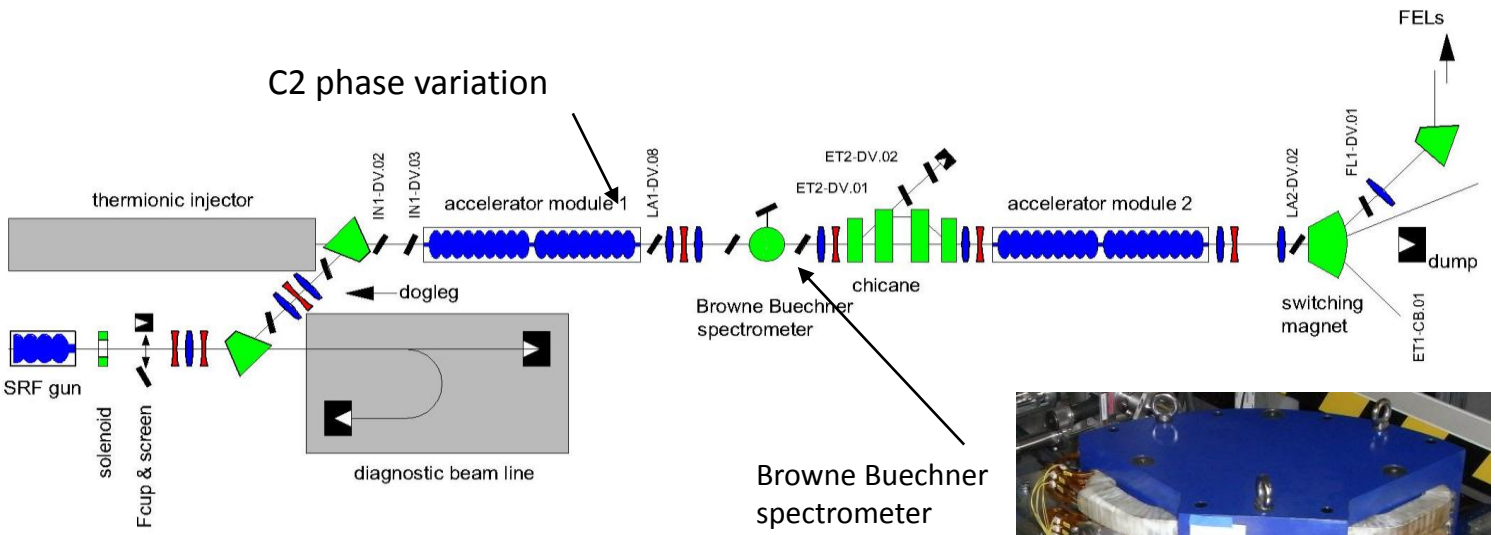
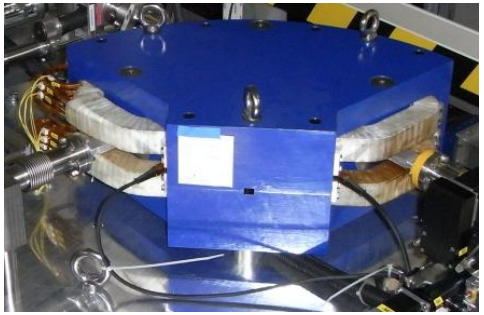
longitudinal phase ellipse — phase scan technique





cavity transport matrix

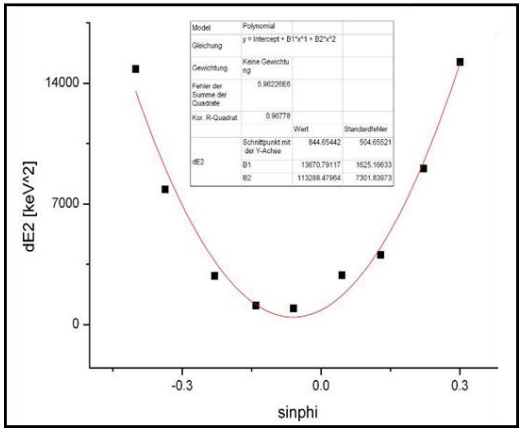
$$R_{C2} = \begin{pmatrix} 1 & 0 \\ -\omega_{RF} V_{C2} \sin(\varphi_{C2}) & 1 \end{pmatrix}$$

longitudinal β function

$$\sigma_E^2(1) = \tau_{22}(0) - 2\tau_{12}(0) V_{C2} \sin(\varphi_{C2}) + \tau_{11}(0)(V_{C2} \sin(\varphi_{C2}))^2$$

$$\sqrt{\tau_{11}} = \sigma_t \ \ rms\ bunch\ length\ (ps)$$

$$\sqrt{\tau_{22}} = \sigma_E \ \ rms\ energy\ spread\ (keV)$$



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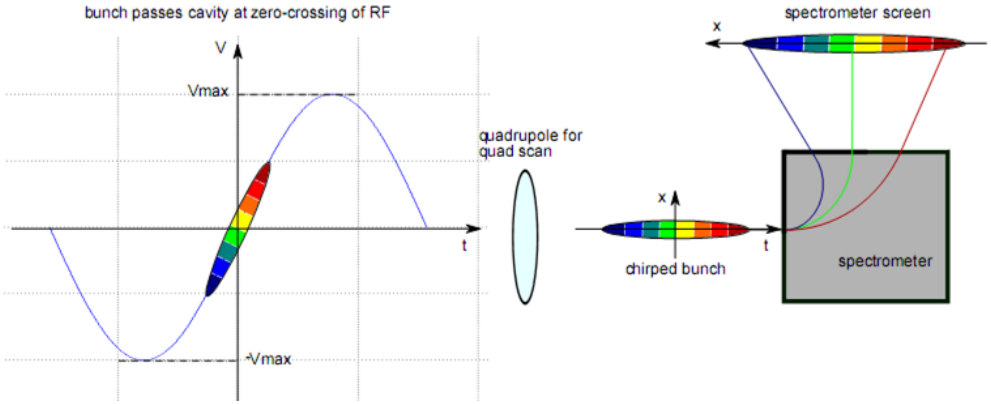
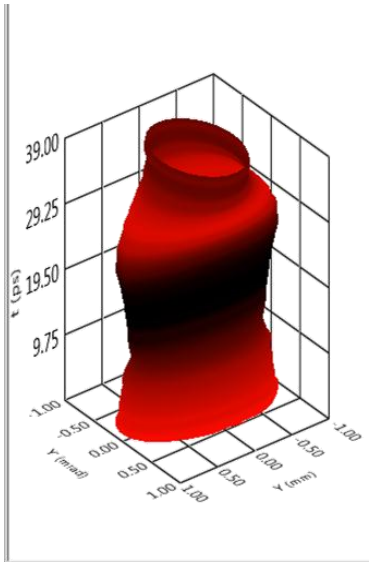
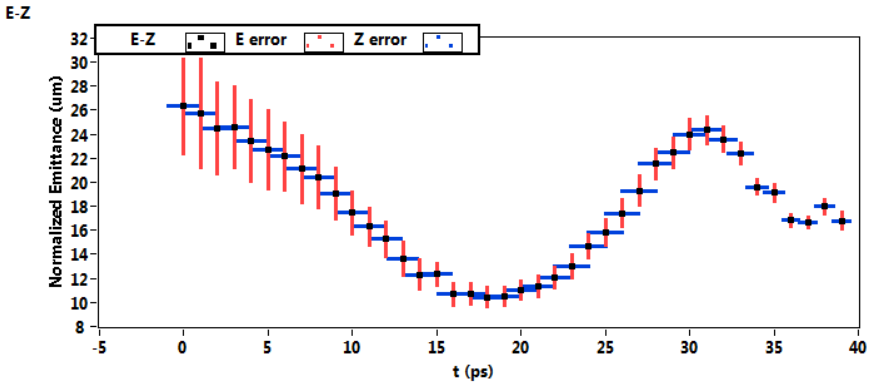
slice emittance measurement

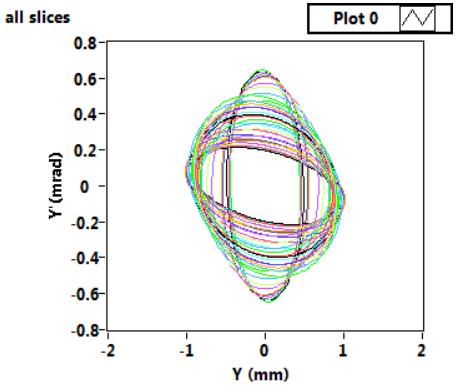
Quadrupole scan + Browne-Beuchner energy spectrometer





- linear chirp: time → energy
- Energy spectrometer: energy → transverse position
- Measure the emittance of different sections by quadrupole scan





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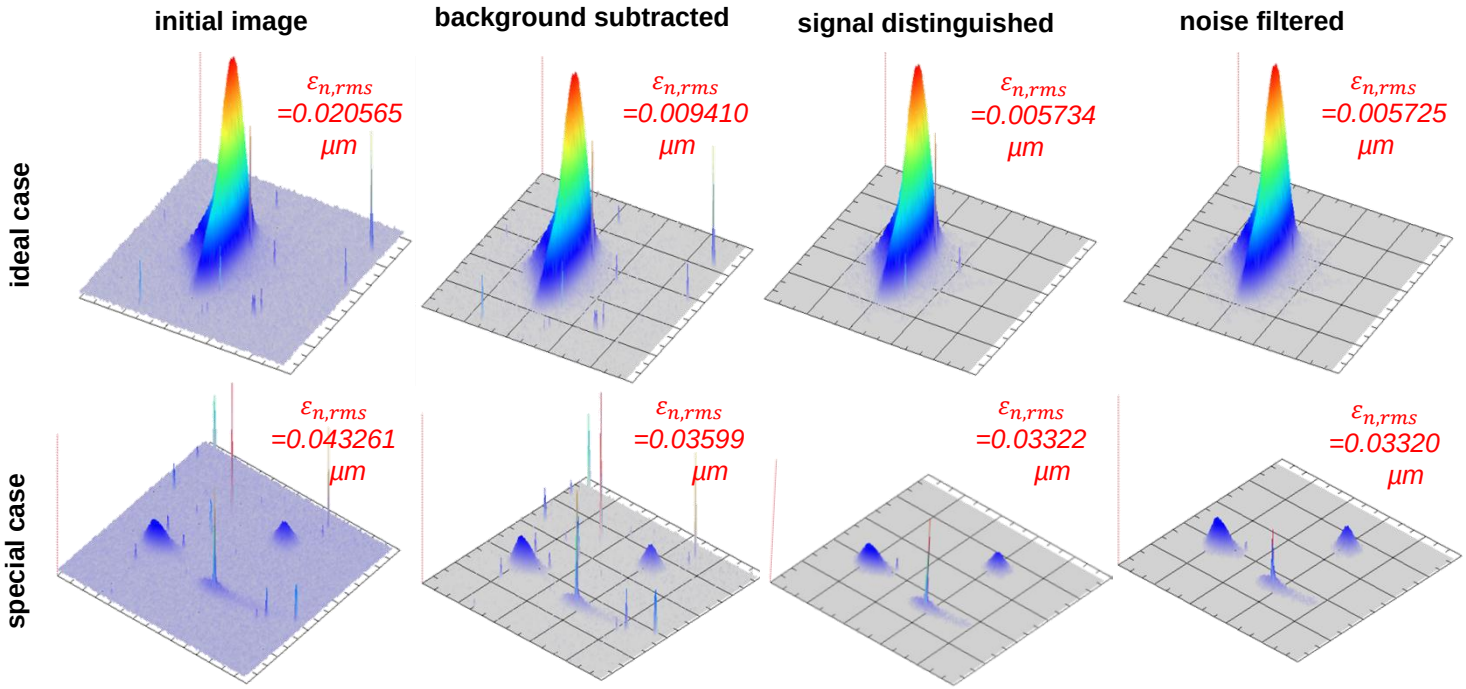
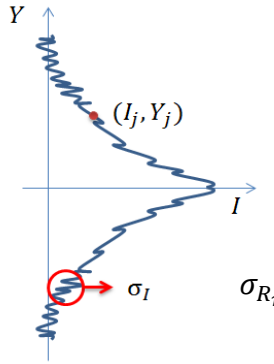
- Universal image processing



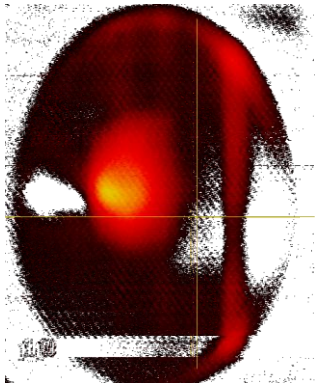
- error estimation



$$R_{rms} = \frac{\sum Y_j I_j}{\sum I_j}$$

$$\sigma_{R_{rms}} = \sqrt{\sum \left(\frac{\partial R_{rms}}{\partial I_j}\sigma_I\right)^2} = \frac{\sigma_I}{\sum I_j}\sqrt{\sum (Y_j - R_{rms})^2}$$

- Reflections



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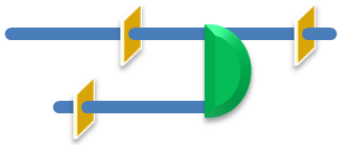
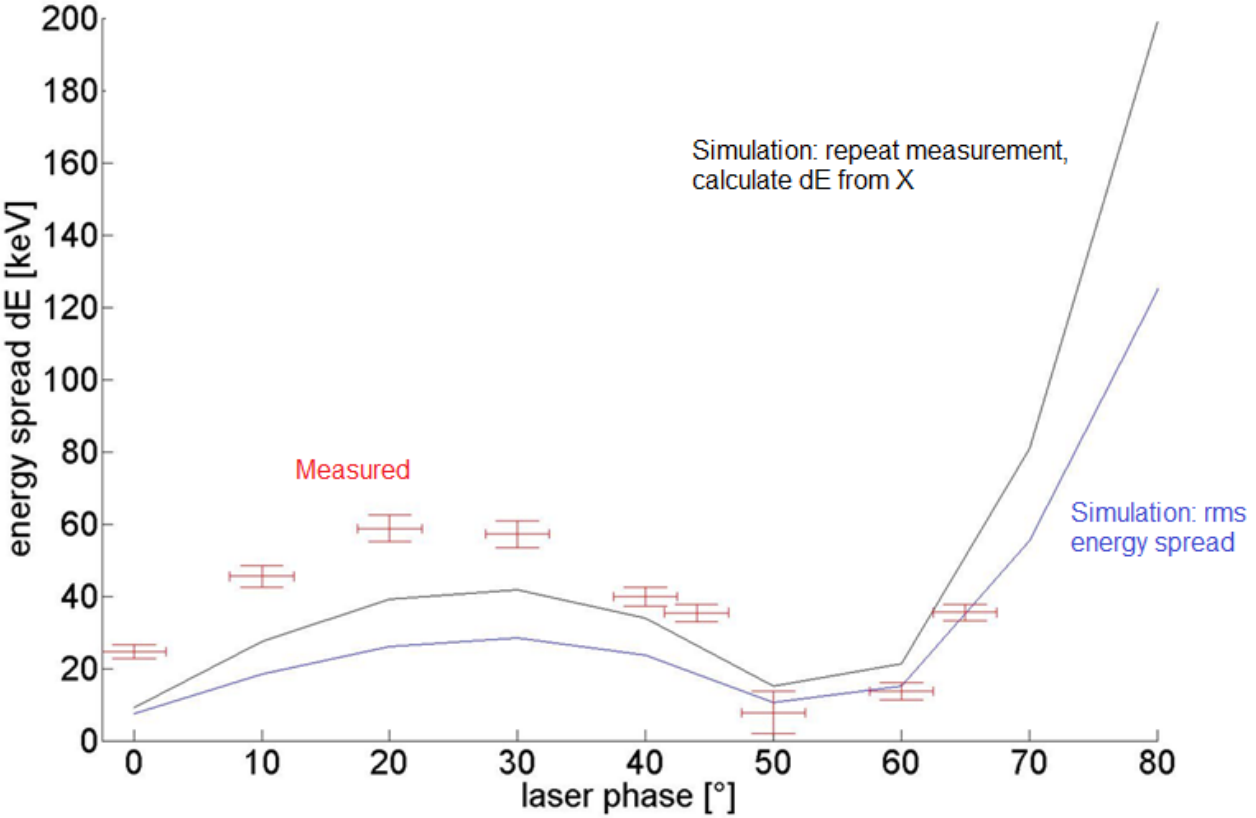
SRF gun energy & energy spread

180° magnet measurement. $\sigma_E = \sqrt{{\sigma_M}^2 - {\sigma_T}^2}$





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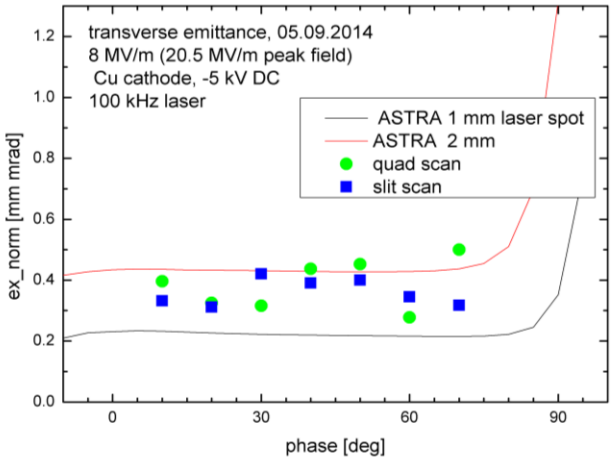
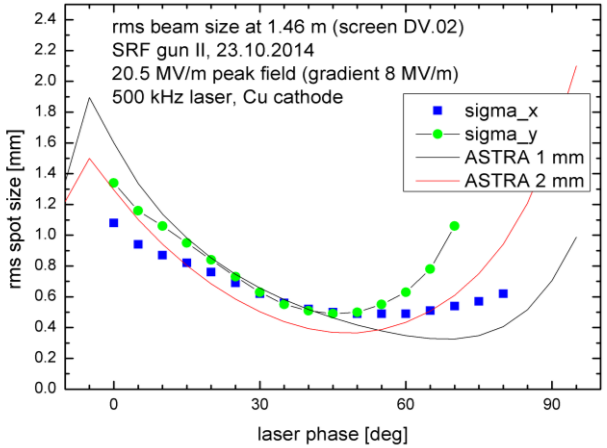
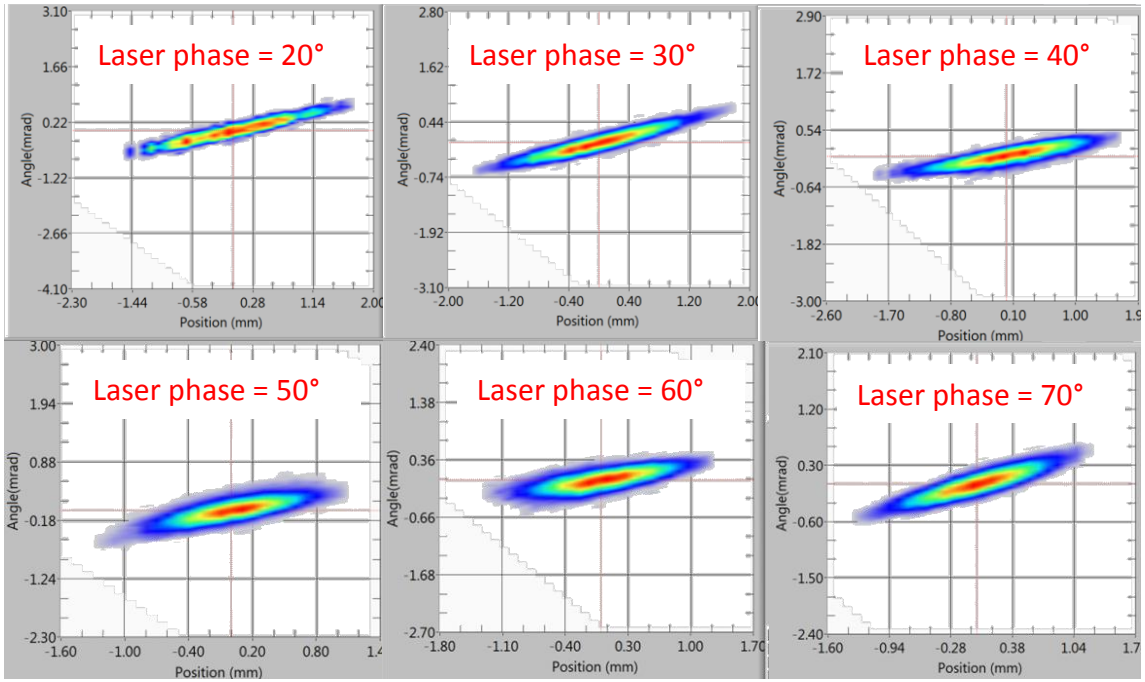
emittance measurement

Cu Cathode measurement







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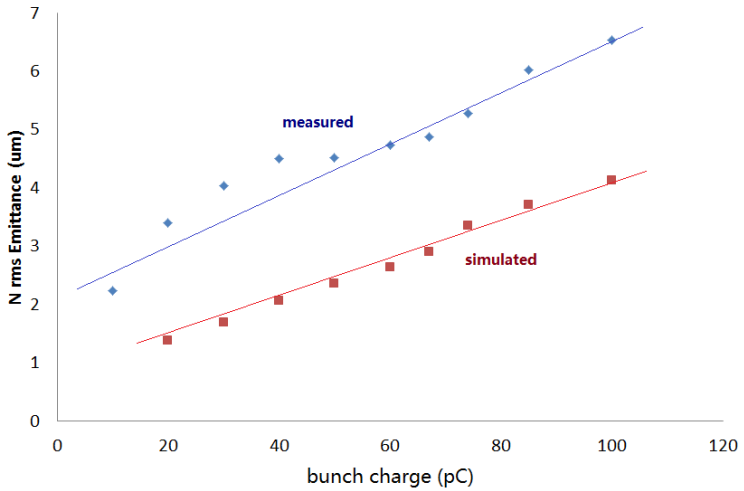
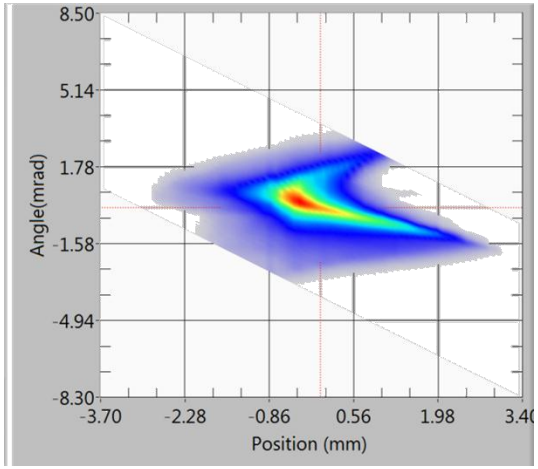
emittance measurement

Ce_2Te Cathode measurement, 100kHz laser, 5ps rms pulse length



40 pC beam on the screen

40 pC beam phase space



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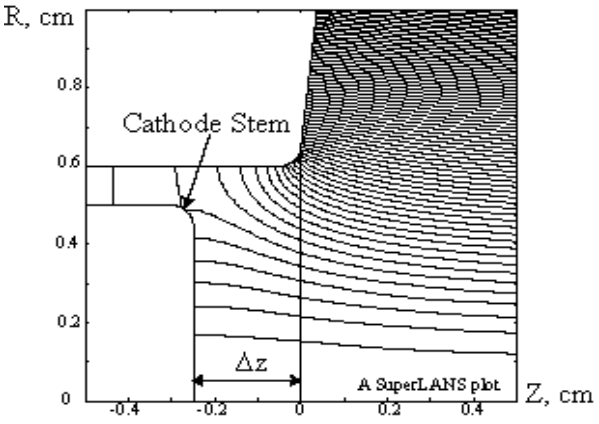
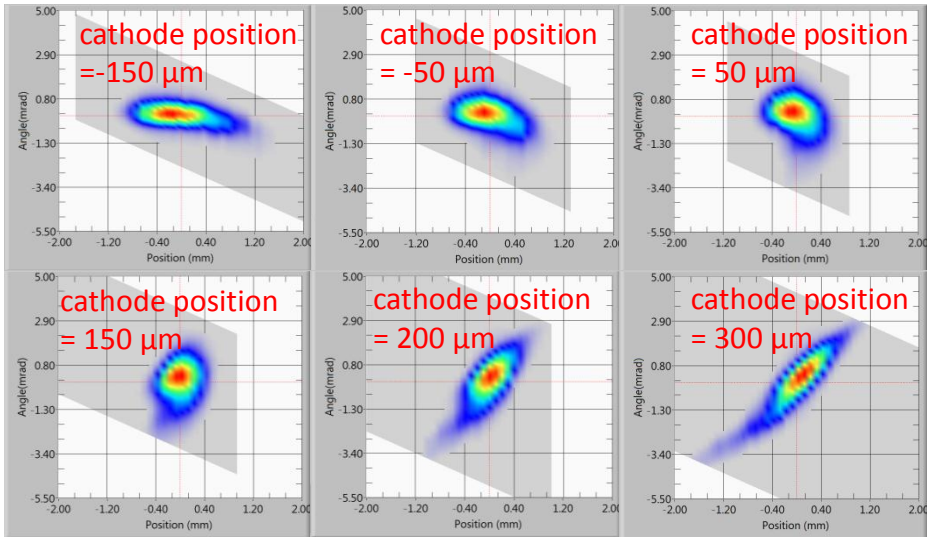
emittance measurement

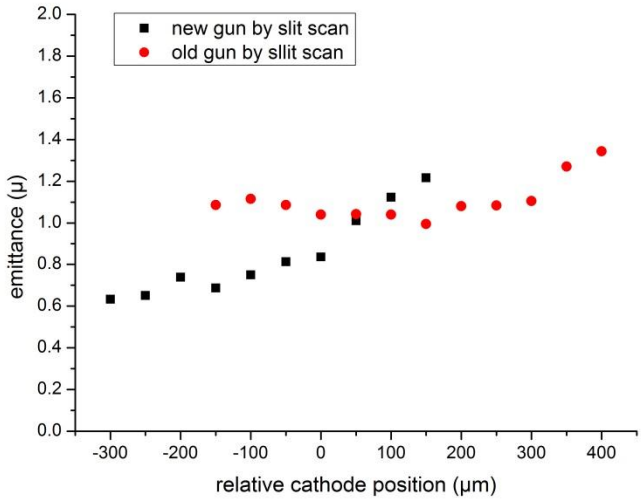
"emittance compensation" research

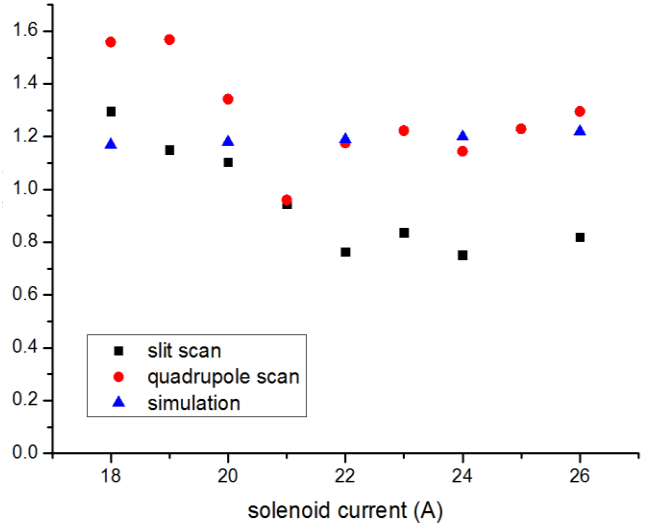
for 10 MeV, 25 $\frac{\mathrm{MV}}{\mathrm{m}}$, 1 nC, $\Delta z = 2.5$ mm,

4.2 mm mrad $\Rightarrow$ 0.98 mm mrad)









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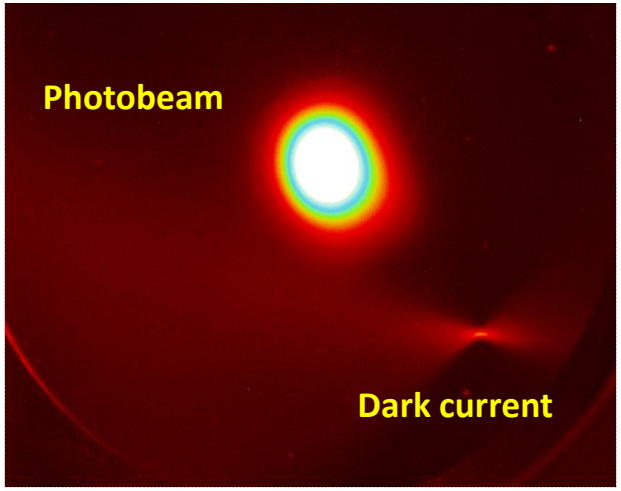
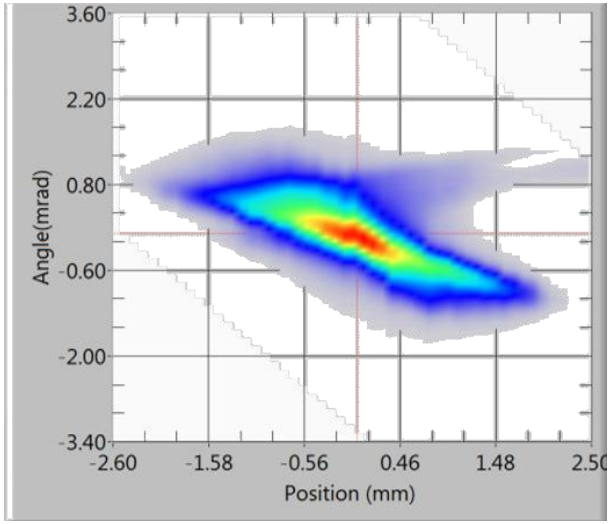
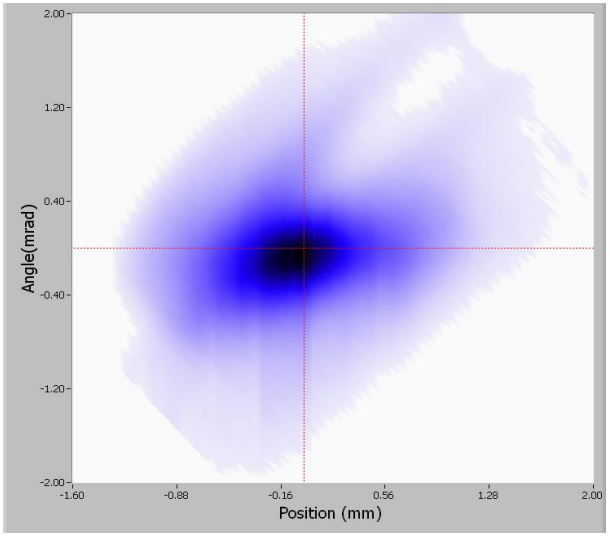
Dark current phase space measurement







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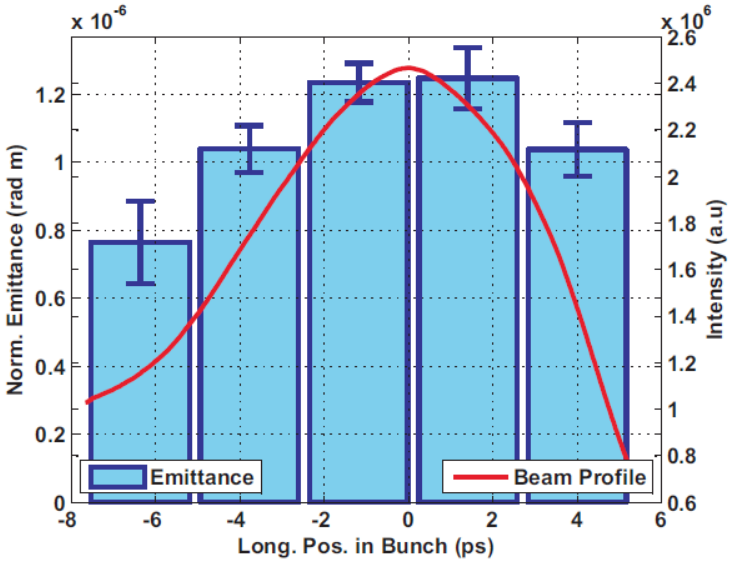
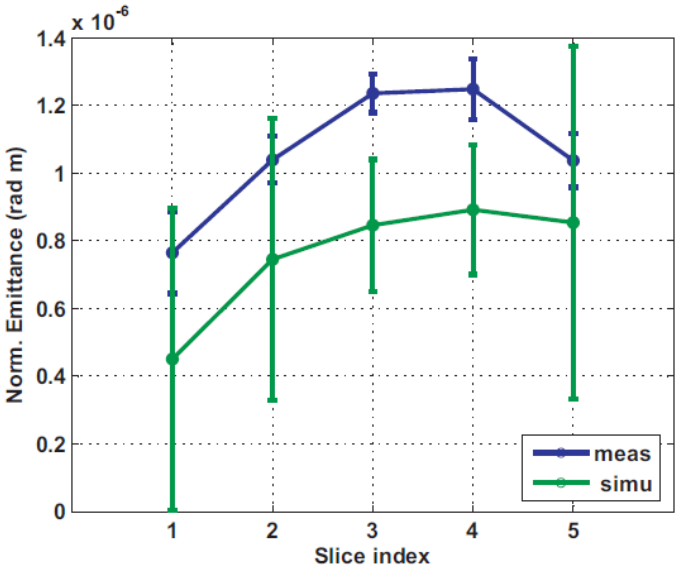
slice emittance measurement





by Dr. Jeniffa Rudolph:

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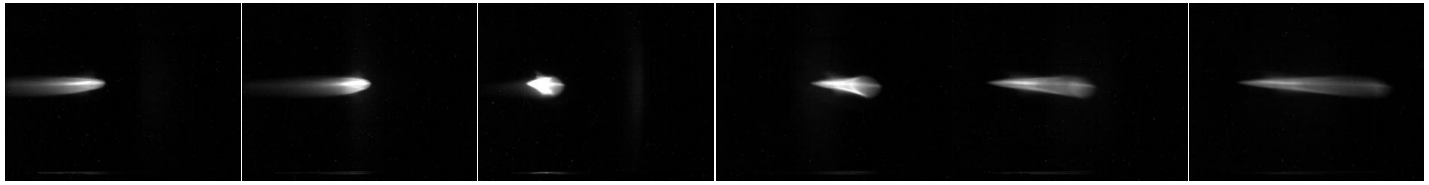
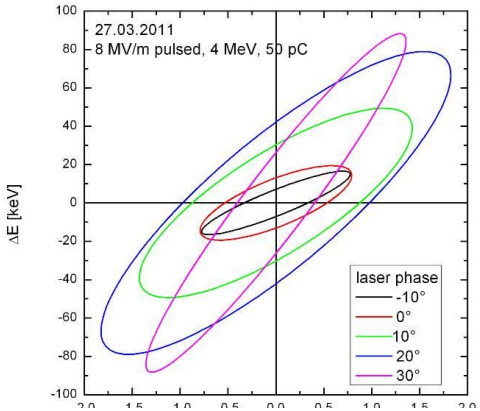
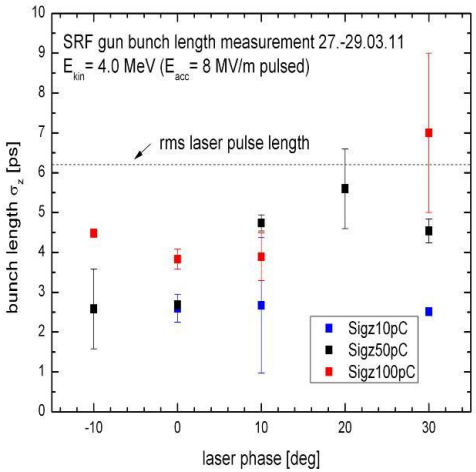
bunch length measurement

Browne Buechner spectrometer pictures

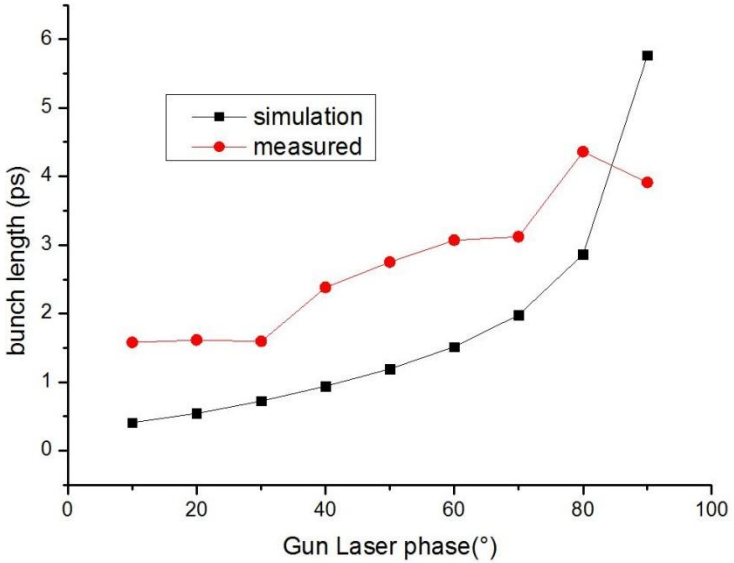


old gun measurement





new gun measurement



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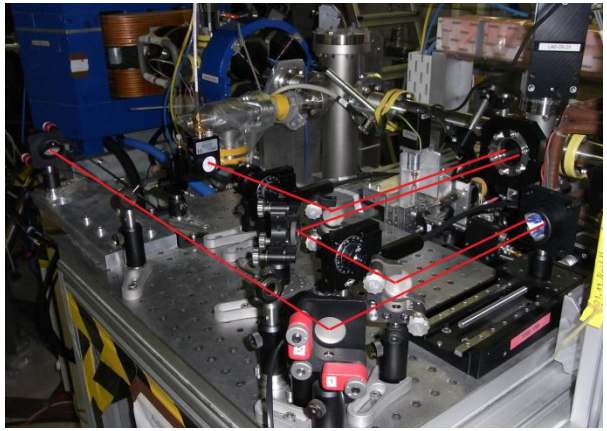
outlook

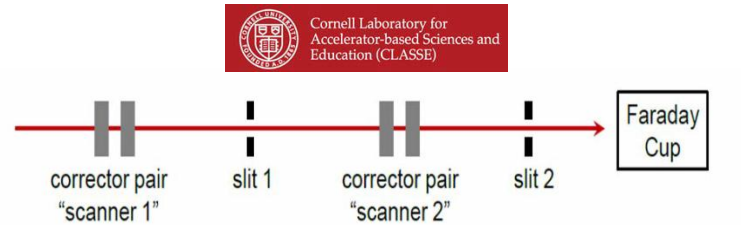
For the current measurements

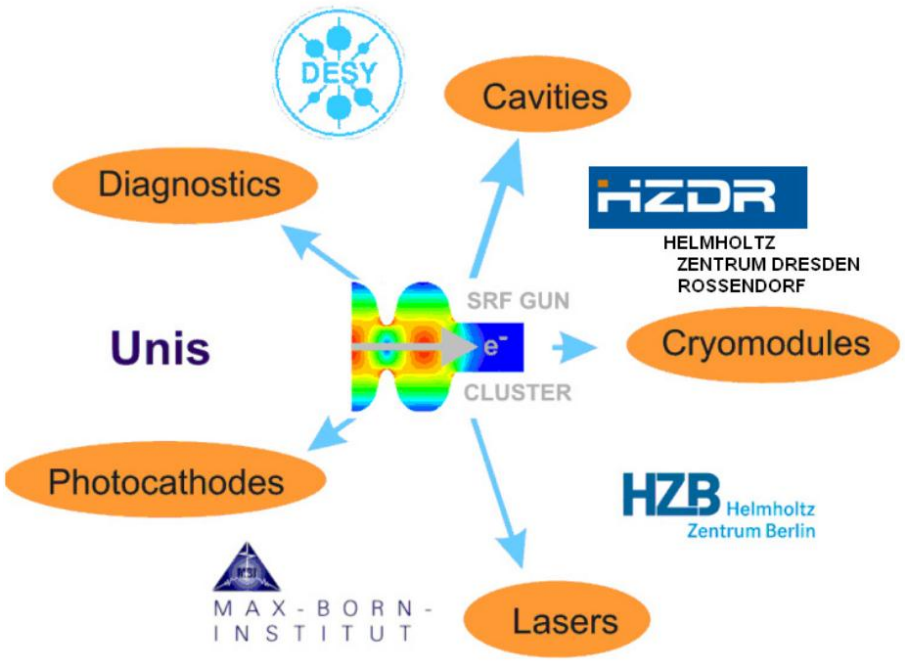
- Update the WinCC control system. Automate the measurements.
- optimize the screen + camera system.
- reduce the influence from system instability.

Interest to new technology

- Longitudinal: electro optic technology, deflecting cavity.
- Transverse: scan the beam rather than the slit.







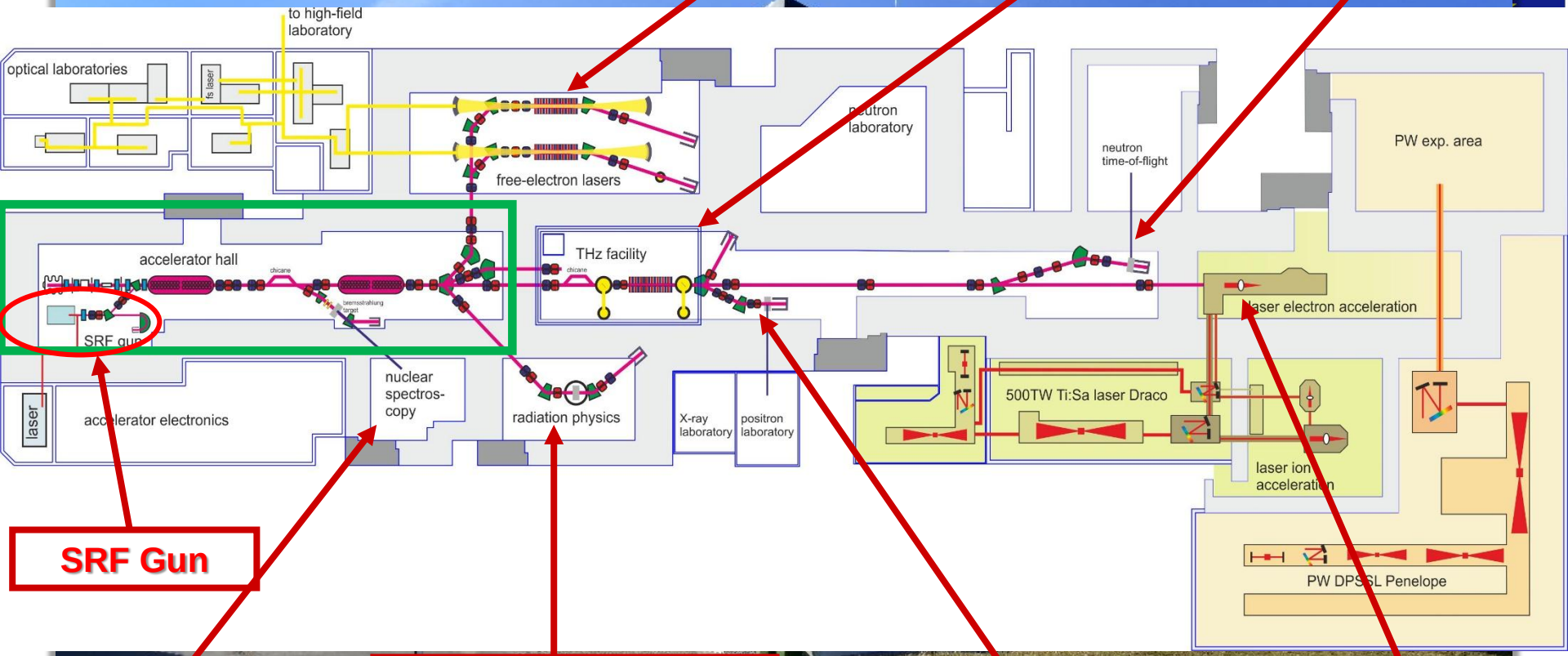
Thank you for your attention!

1mA, 40MeV CW electron accelerator

coherent IR-radiation
3 – 230 µm

THz radiation
100 µm – 3 mm

neutron time of flight
E_n 0 – 10 MeV



SRF Gun

Bremsstrahlung
0 – 17 MeV

ELBE elctrons/ monochromatic X-rays
30 – 34MeV/10 – 100 keV

pulsed, mono-energetic positrons 0.2 – 30 keV

electron laser interaction