ICS experimental studies in CTF2

CLIC Mini Week

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2. RF-Track simulations of the CTF2 gun
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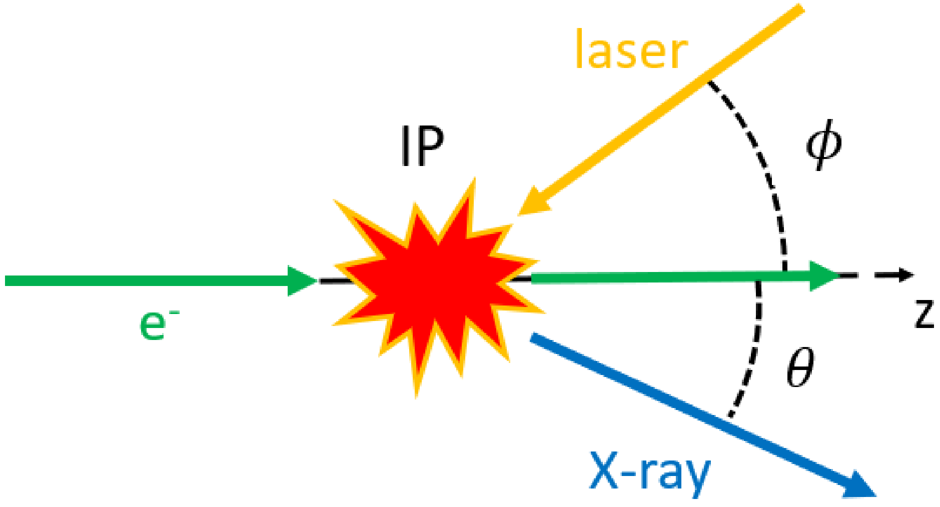
Compton backscattering



= The scattering of a low energy photon from an EM field to a high-energy photon (X-ray or gamma ray) during the interaction with a charged particle.

$$N_\gamma = \sigma_c \frac{N_e N_{\mathrm{laser}} \cos(\phi/2)}{2\pi\sigma_{\gamma,y}\sqrt{\sigma^2_{\gamma,x}\cos^2(\phi/2)+\sigma^2_{\gamma,z}\sin^2(\phi/2)}}$$

Total flux

$$\mathcal{B} = \frac{\mathcal{F}}{4\pi^2\sigma_{\gamma,x}\sqrt{\epsilon_x/\beta_x}\,\sigma_{\gamma,y}\sqrt{\epsilon_y/\beta_y}}$$

Average brilliance

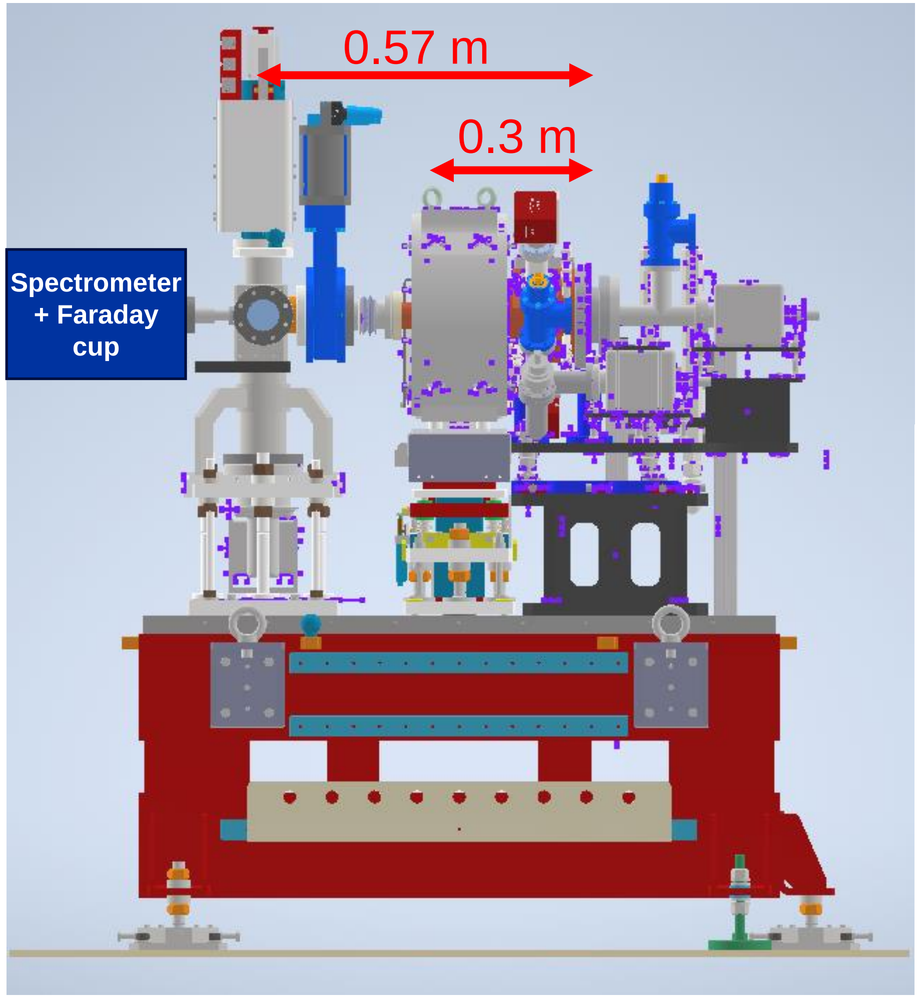
$$\frac{\sigma_{E_\gamma}}{E_\gamma} = \sqrt{\left(\frac{\sigma_{E_\theta}}{E_\theta}\right)^2 + \left(2\frac{\sigma_{E_e}}{E_e}\right)^2 + \left(\frac{\sigma_{E_{\mathrm{laser}}}}{E_{\mathrm{laser}}}\right)^2 + \left(\frac{\sigma_{E_\epsilon}}{E_\epsilon}\right)^2}$$

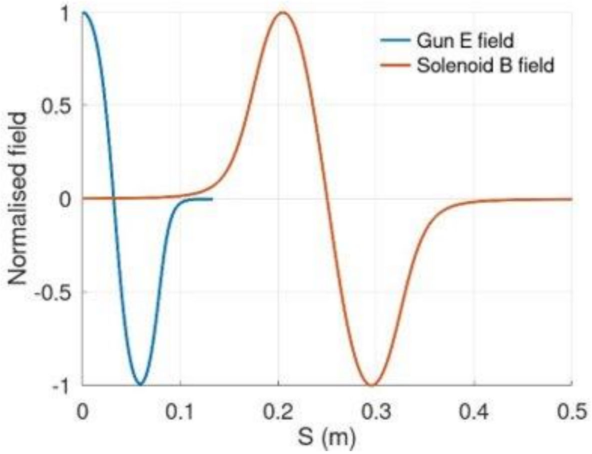
Photon bandwidth

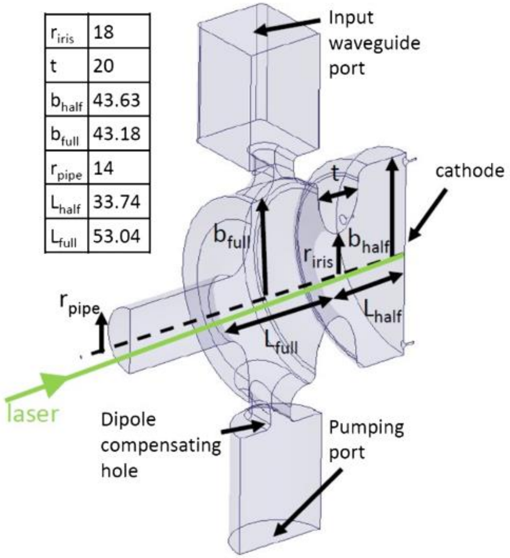
$$E_{\mathrm{X\text{-}ray}} = 2\gamma^2 E_{\mathrm{laser}} \frac{1+\cos\phi}{1+\gamma^2\theta^2}$$

Photon energy

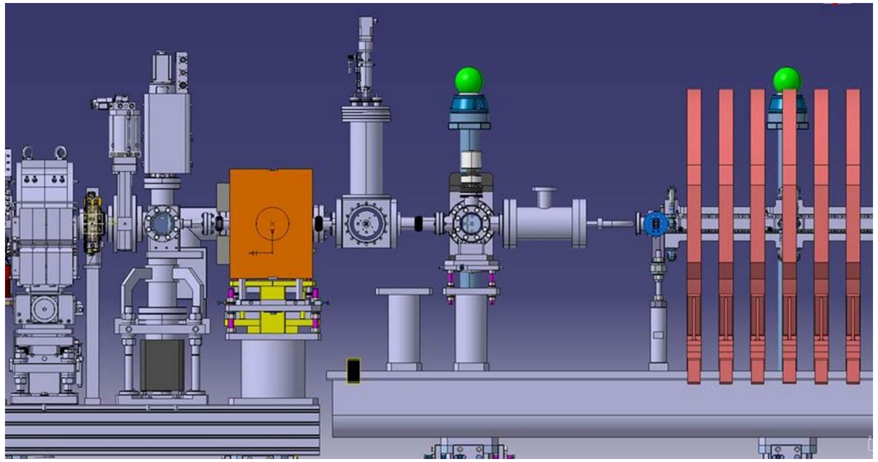
The CTF2 gun







r_{iris}	18
t	20
b_{half}	43.63
b_{full}	43.18
r_{pipe}	14
L_{half}	33.74
L_{full}	53.04

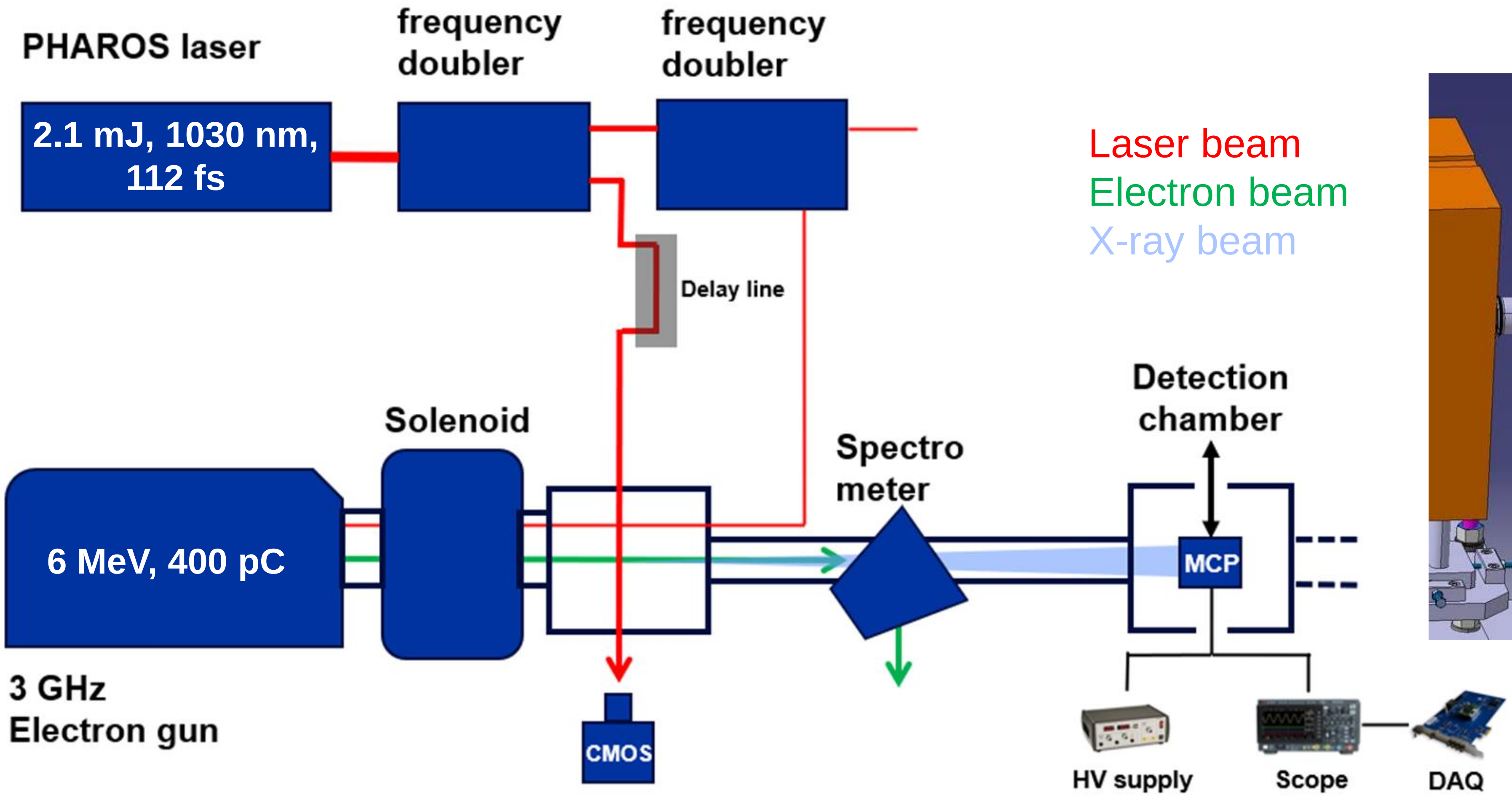


CLINXBT_0001

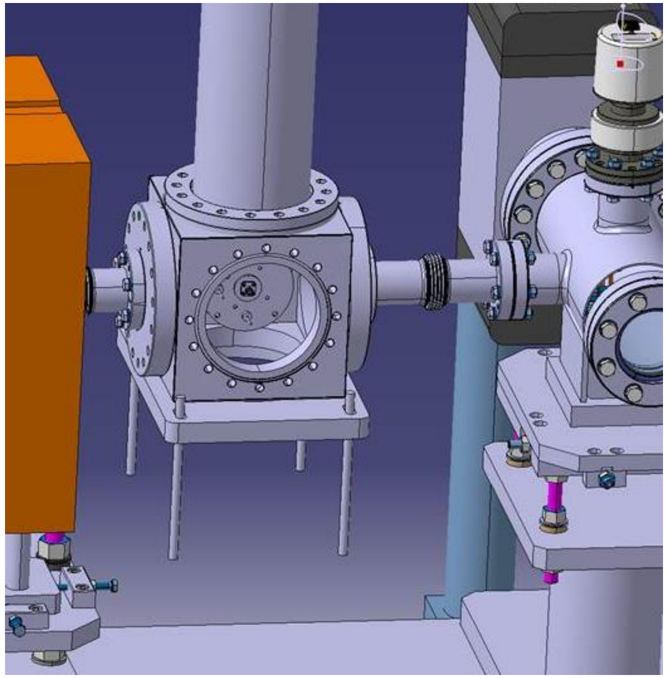
- **S-band standing wave 1.5 cell RF-gun intended for the new AWAKE injector.**
- **Prototype constructed by INFN-Frascati and commissioned at CTF2.**
- **Fabricated with brazing free technology [1].**

[1] D. Alesini, et al., PRAB, vol. 21, n. 11, November 2018

Experimental set-up



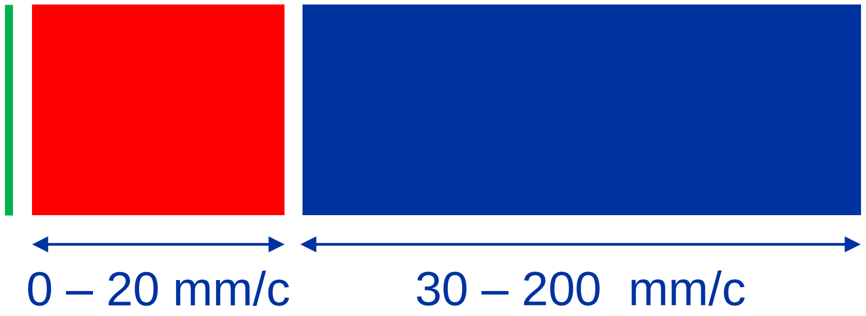
Laser beam
Electron beam
X-ray beam



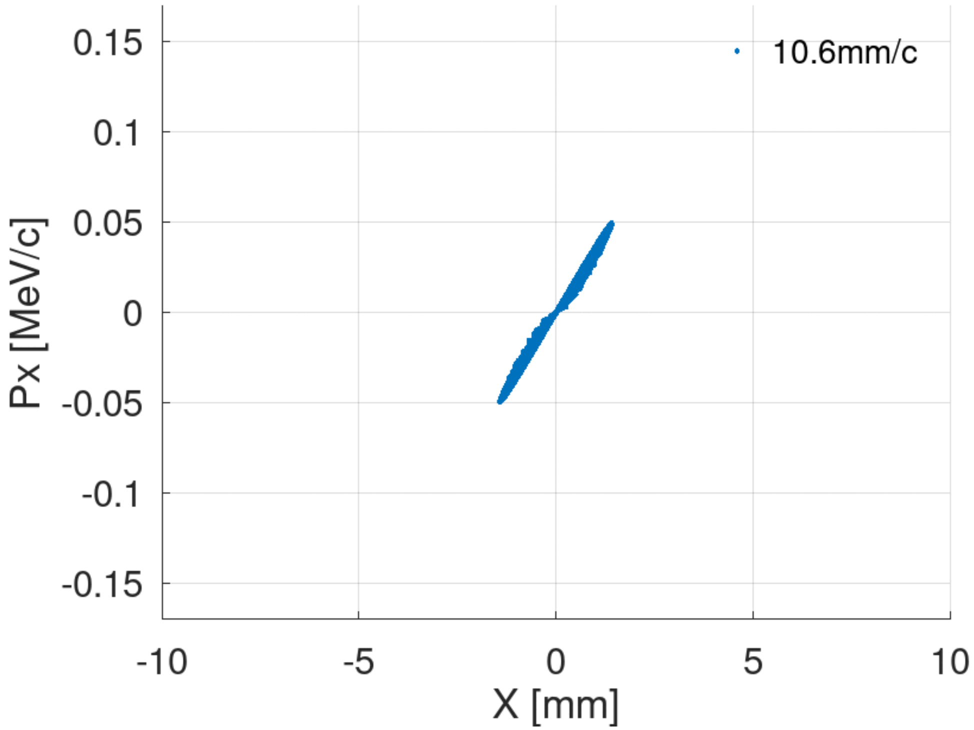
Gun simulations

Simulations of CTF2 injector

- A model of the CTF2 gun was implemented in RFT. The model comprised the cathode, gun, and solenoid.
- Optimisation goals:
  - Maximise flux
  - Minimise background

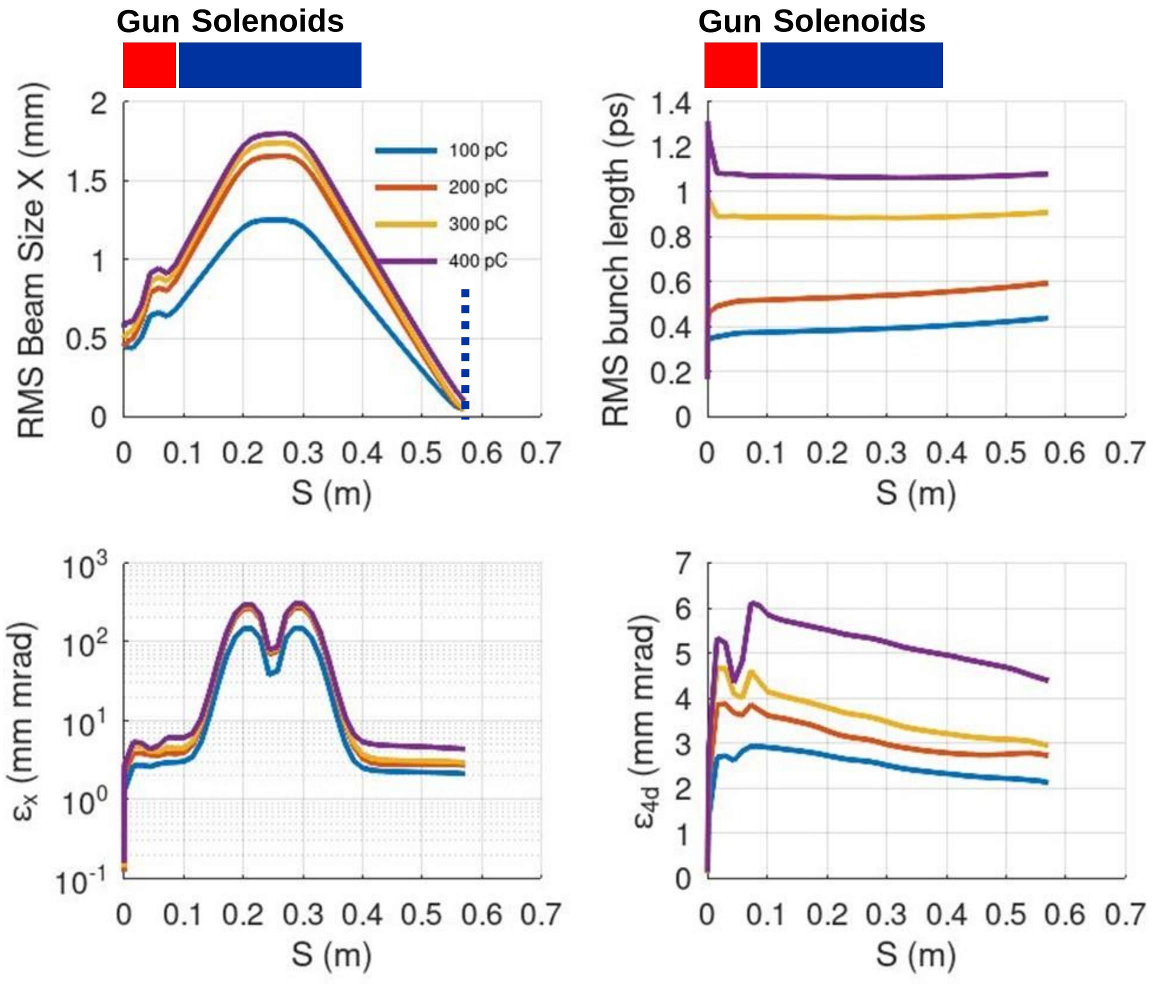


Evolution of the phase space from cathode to screen



Cathode	Gun	Solenoid
Bunch charge (laser intensity)	RF phase	B field
Laser spot size (Gaussian)	RF gradient	

Results: Flux optimisation (cathode → screen)



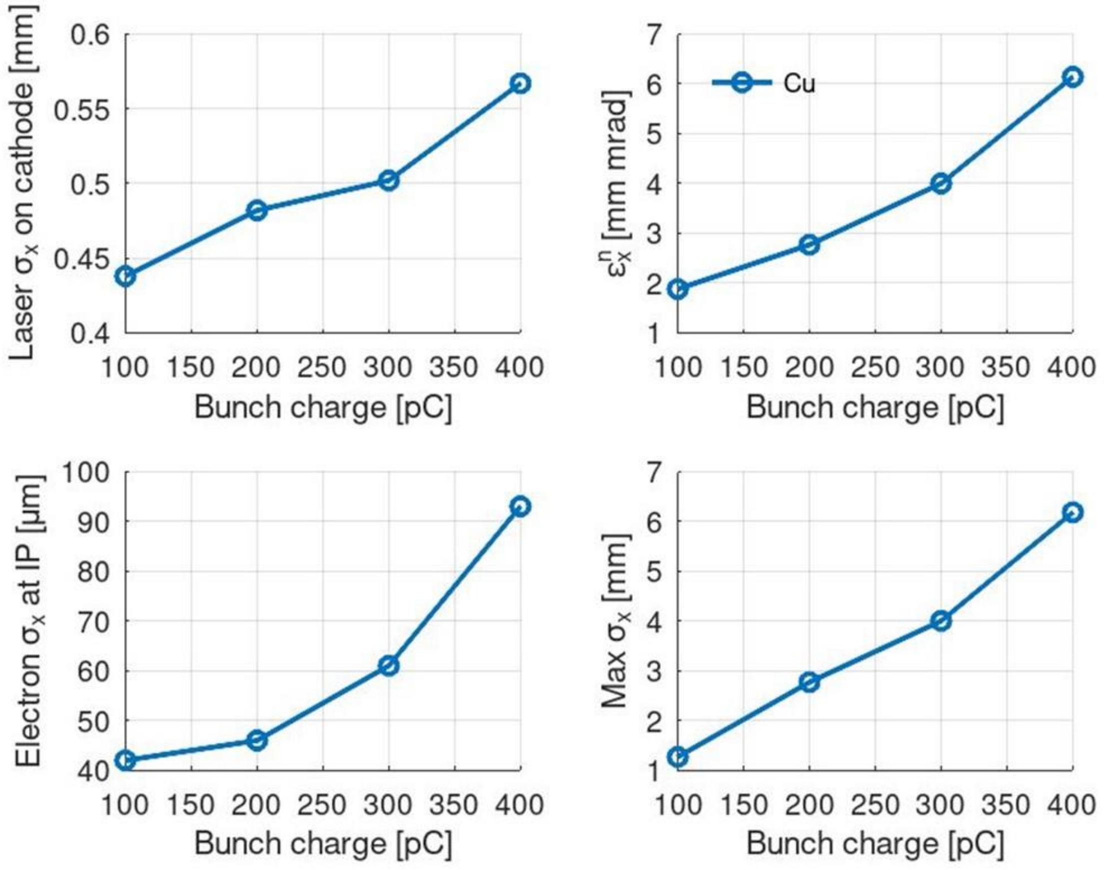
Setup	Unit	100 pC	200 pC	300 pC	400 pC
Gun phase (RFT)	Deg	100.5	108.5	99.0	94.0
Gun gradient	MV/m	120	120	120	120
Max B field	T	0.350	0.355	0.350	0.336
Laser RMS size	mm	0.438	0.482	0.502	0.567

Parameter at IP	Unit	100 pC	200 pC	300 pC	400 pC
Beam energy	MeV	5.77	5.84	5.77	5.75
ϵ_x^n	mm mrad	1.88	2.77	4.00	6.14
$\sigma_{el,\,max}$	mm	1.27	1.68	1.78	1.80
$\sigma^*_{x,el}$	µm	42	46	61	94
$\sigma^*_{z,el}$	ps	0.4	0.6	0.90	1.1
Ph/bunch	#	14,000	35,000	37,000	29,000

On-crest phase in RFT: 120°

Distance from cathode to IP = 0.57 m

Results: Flux optimisation (cathode → screen)



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On-crest phase in RFT: 120°

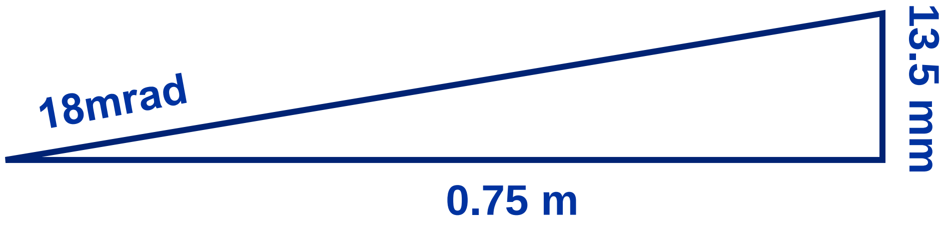
Distance from cathode to IP = 0.57 m

Optimal beam parameters

Electron beam parameter	Value
Beam energy	5 MeV
Bunch charge	400 pC
RMS beam size at IP	94 µm
RMS bunch length	1 ps
Repetition rate	10 Hz

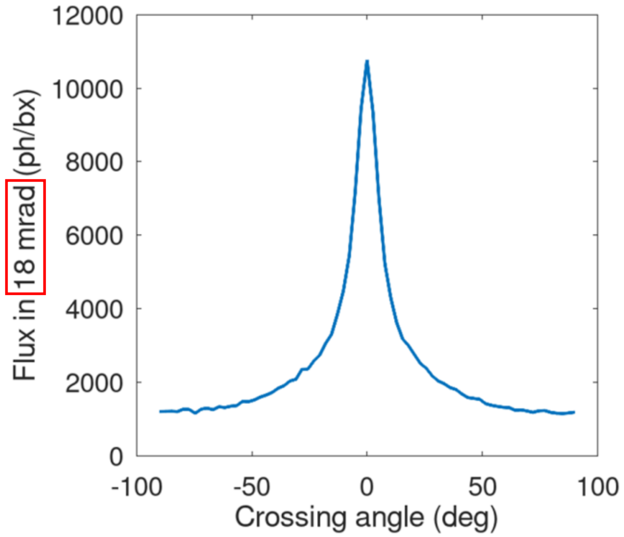
Laser beam IP parameter	Value
Wavelength	1030 nm
Laser pulse energy	0.9 mJ
RMS pulse length	112 fs
M2	1.3
Laser waist at IP	15 µm

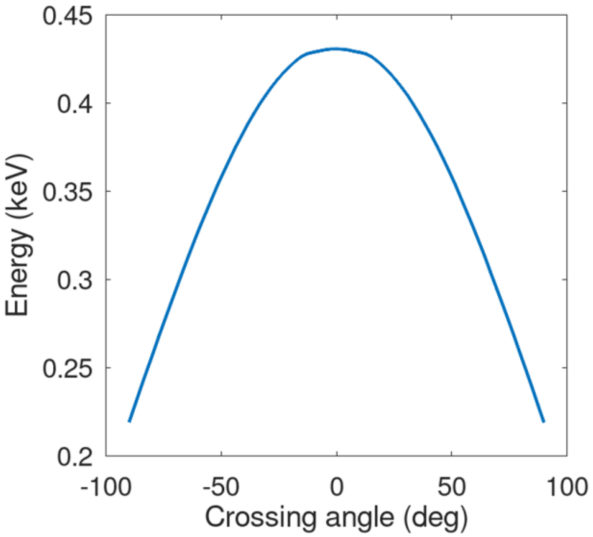
Input parameters	Value
Laser RMS on cathode	0.56 mm
Gun solenoid field	0.3 T
Gun phase	$-20°$ (wrt on-cr st)
Gun field	100 MV/m



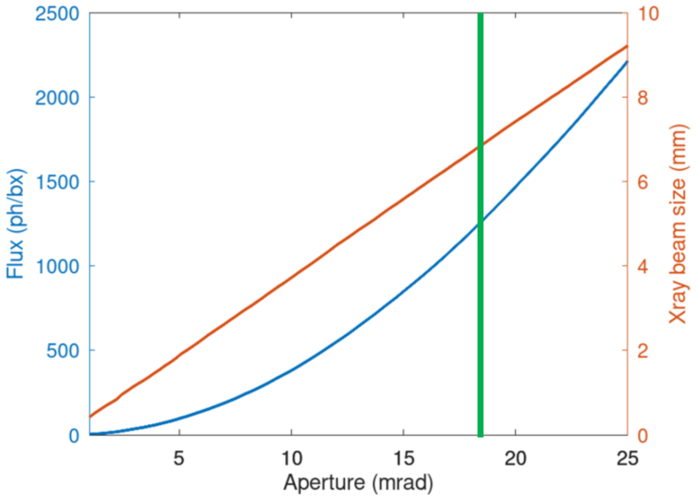
Collection angle of photon detector

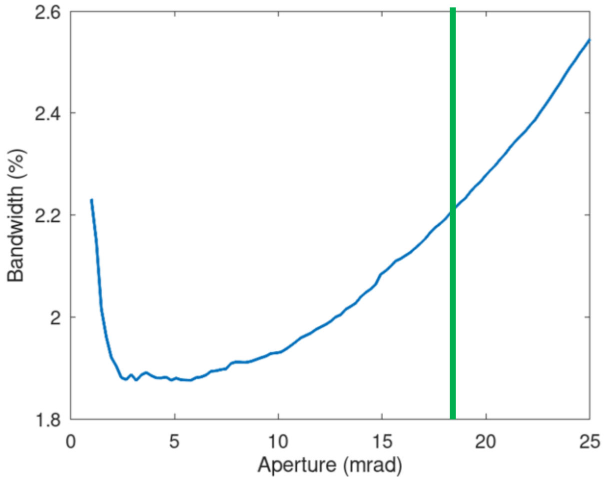
Simulated X-ray parameters

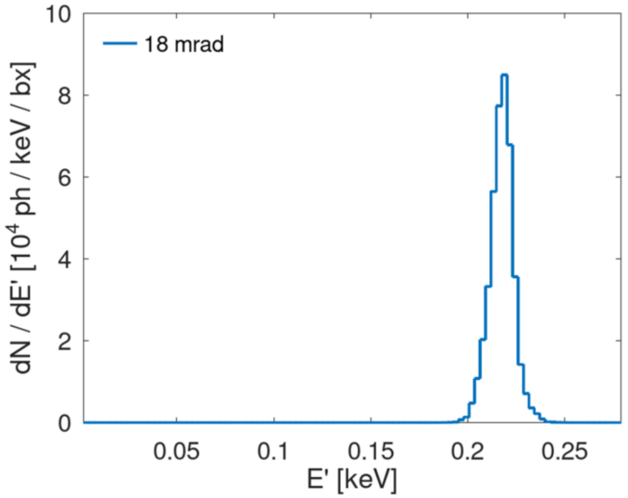




X-ray beam parameter	Value
Photon energy	220 eV
Wavelength	5.6 nm
Crossing angle	90
RMS beam size on detector	6.7 mm
RMS pulse length	0.23 ps
Nb photons per pulse (total)	29,000
Nb photons per pulse (18 mrad)	1,200
Bandwidth	2.2%

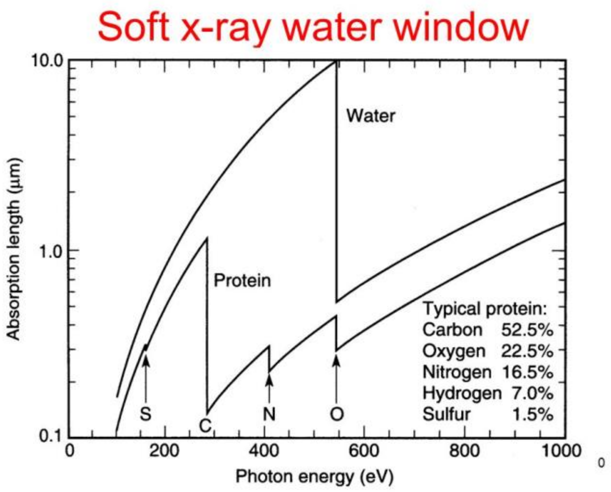






Water Window X-ray source

- Water window is a region in the electromagnetic spectrum where water is invisible.
- The region spans the K-edge of Carbon (282 eV) to Oxygen (533 eV).
- Only microscopy allowing for 10 nm range 3D imaging of cellular samples in their near-native state → quantitative characterisation of (sub)cellular organisation in single cells and cell-cell interaction [1].
- Most water window microscopes have been implemented as part of synchrotrons.



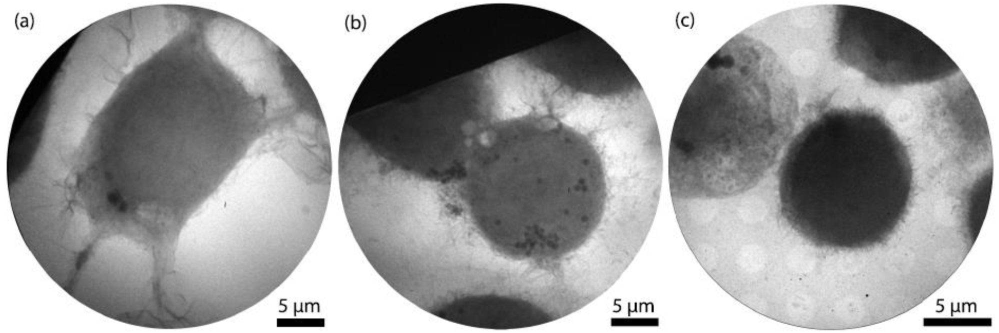


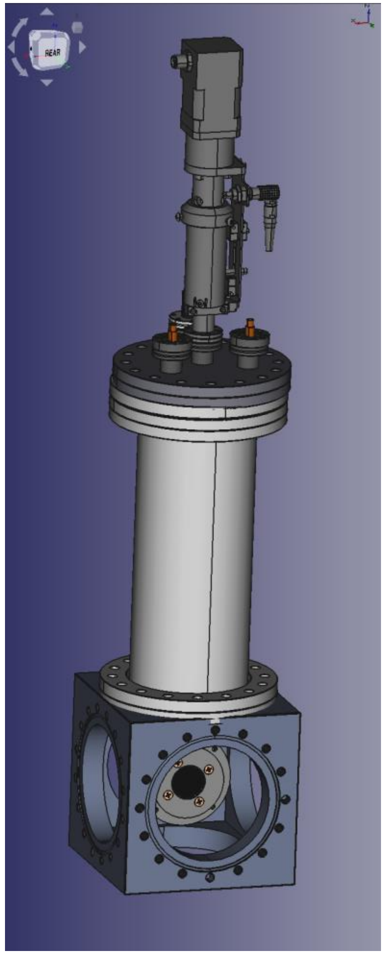
Fig. 9. 2D cryo imaging with laboratory soft XRM. (a) Healthy and adhered HEK 293 T cell, 30 s exposure time; (b) slightly starved and rounded HEK 293 T cell, 20 s exposure time; (c) THP-1 cells with 5 min exposure time. Images (a) and (b) from the Stockholm microscope and (c) from the Berlin microscope.

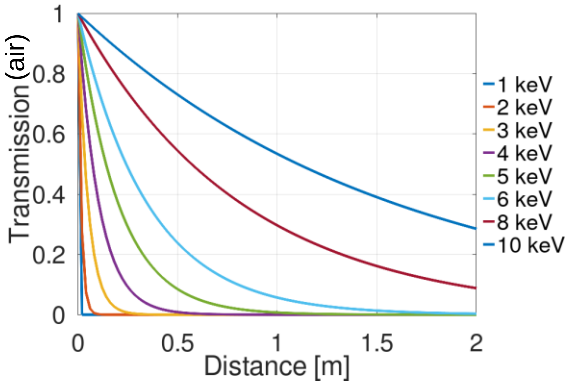
https://doi.org/10.1364/OPTICA.393014

[1] V. Weinhardt, J.-H. Chen, A. Ekman, G. McDermott, M. A. Le Gros, and C. Larabell, "Imaging cell morphology and physiology using x-rays," Biochem. Soc. Trans. 47, 489–508 (2019).

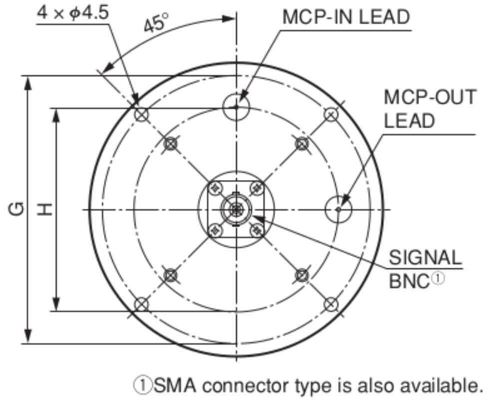
Experimental set-up

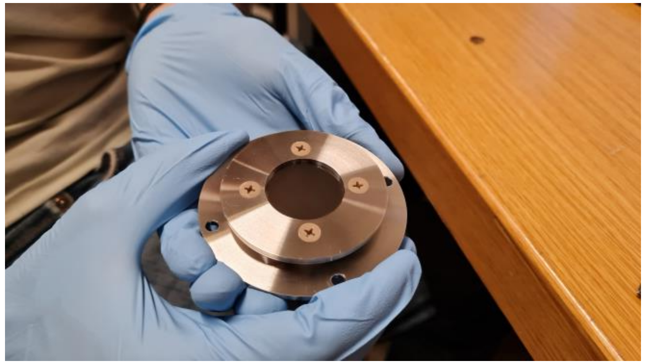
The detector set-up

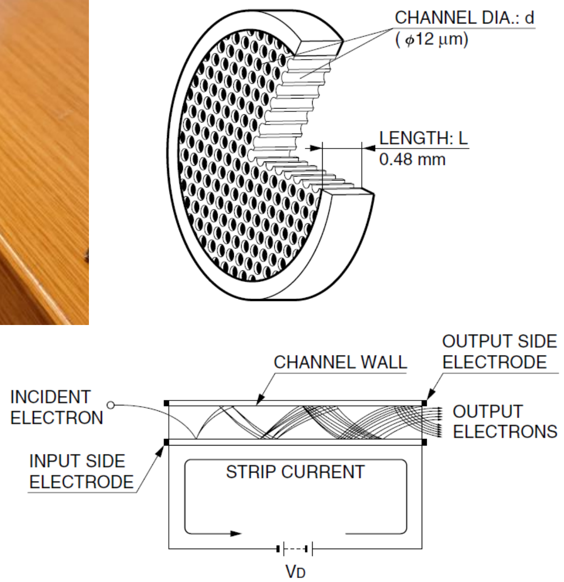




High absorption of soft X-rays <u>in air</u> prevents us from placing the photon detector in-air







Dimensions: 81 by 36 mm

Provides 10^6 gain with a 27 mm effective diameter

Operated in vacuum (< 1e-4 Pa)

Capable of time-of-flight measurements (900 ps FWHM pulse width)

Configuring the CTF2 gun for the ICS experiment

To maximise the scattered photon flux we need:

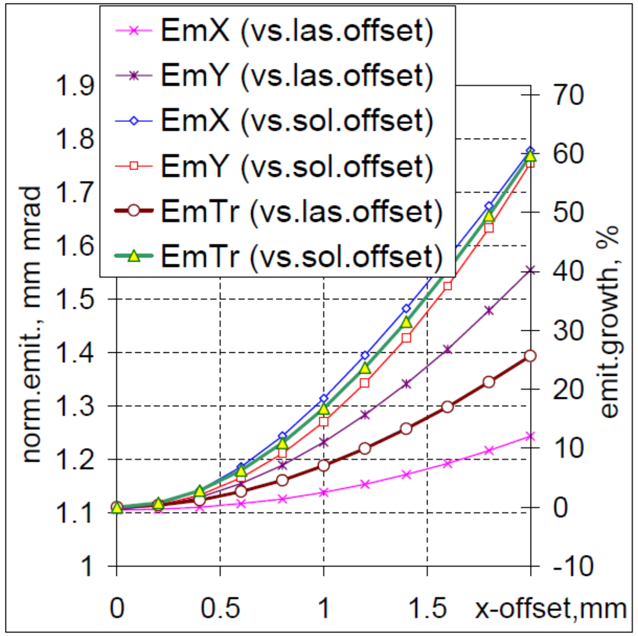
- High bunch charge (> 200 pC)
- High laser pulse energy (1 mJ from frequency doubler)
- Small laser pulse length (100 fs RMS)
- High beam energy to reduce angular spread of ICS photons (> 5 MeV)
- Small spot size (< 150 μm RMS)

As indicated from the optimisation of the simulation:

- Use a small RF phase
- Use a laser spot size with RMS size $\sim 500\ \mu\mathrm{m}$
- Align UV laser beam on the cathode, along with the solenoid

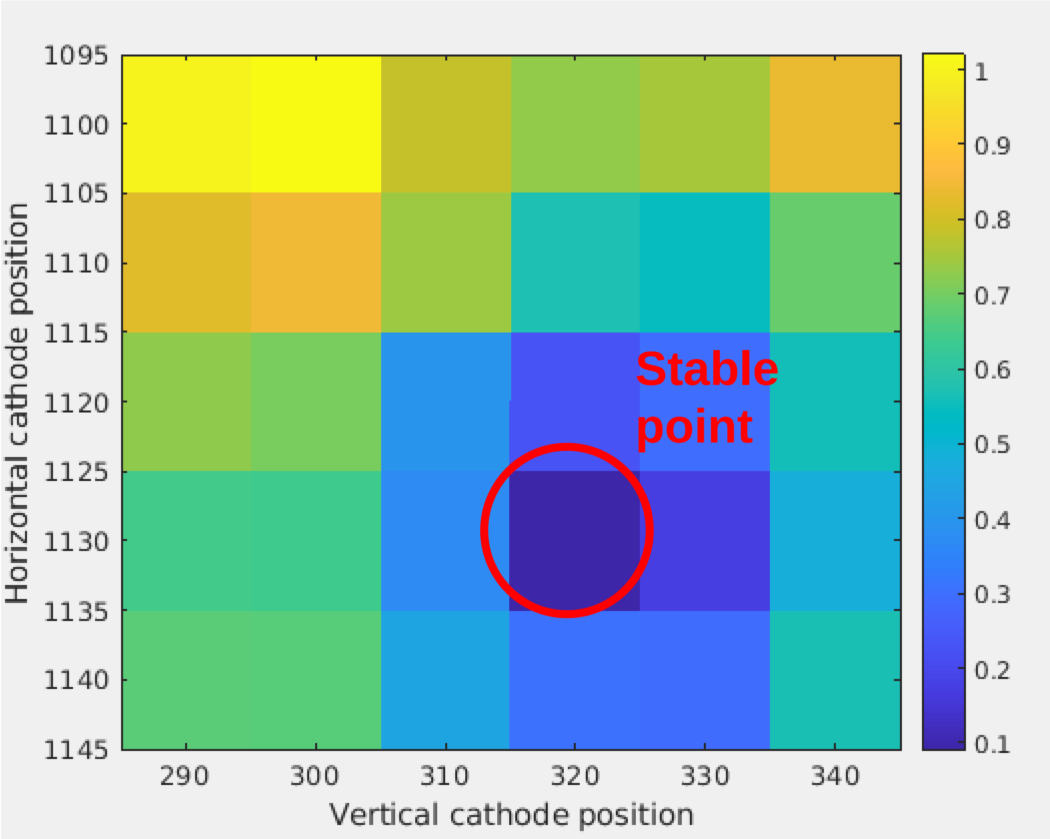
$$N_\gamma = \sigma_c \frac{N_e N_{\text{laser}} \cos(\phi/2)}{2\pi\sigma_{\gamma,y}\sqrt{\sigma_{\gamma,x}^2 \cos^2(\phi/2) + \sigma_{\gamma,z}^2 \sin^2(\phi/2)}}$$

Total flux

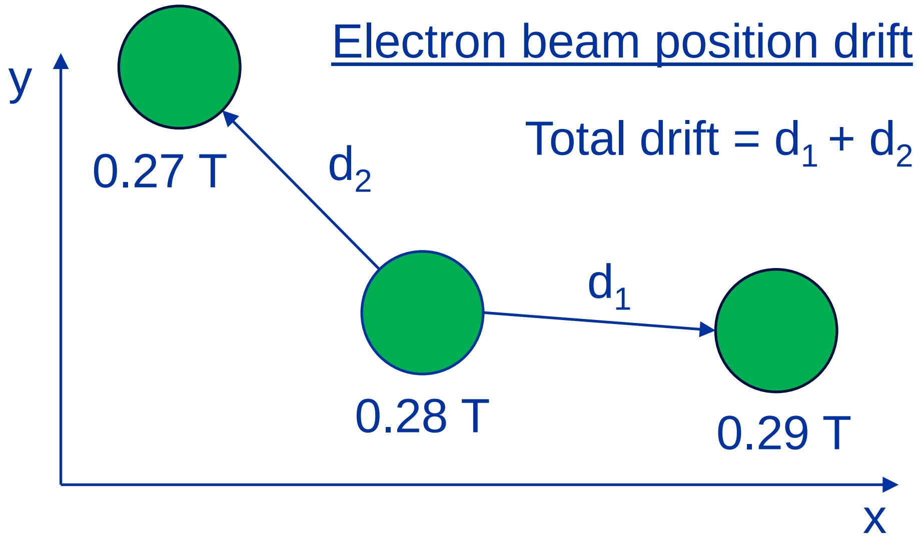


"Beam based procedures for RF guns", PAC2005

Alignment of laser spot on cathode with solenoid

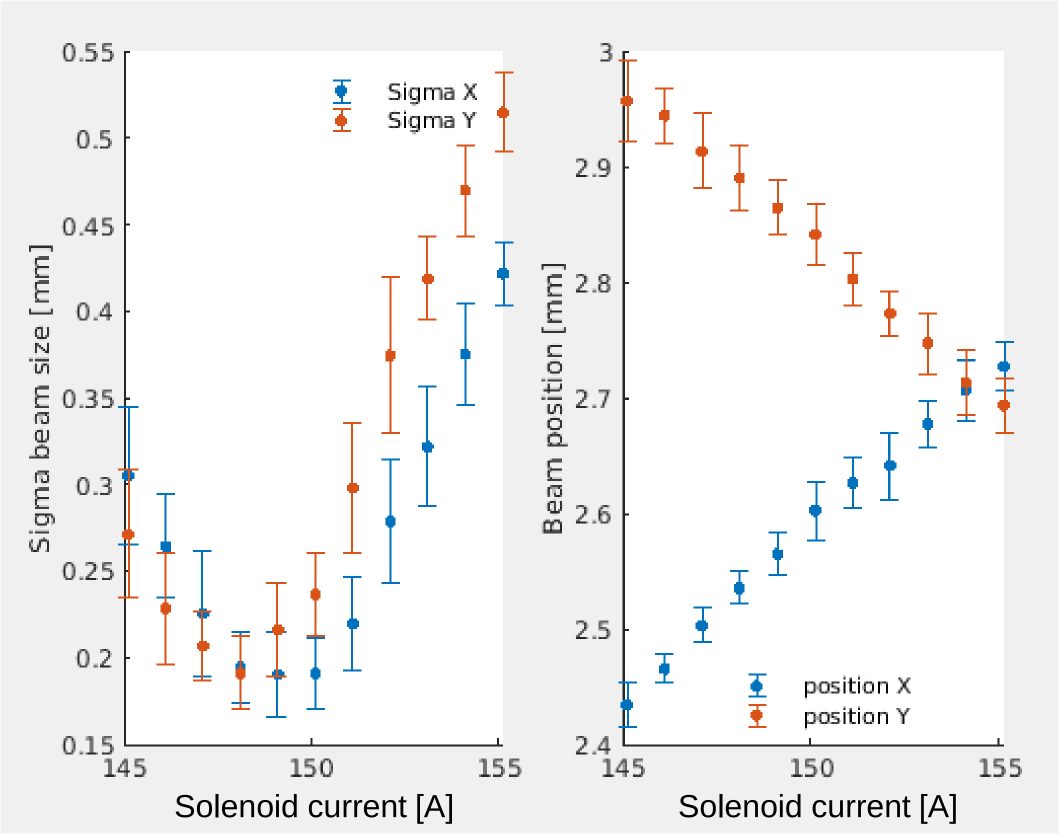


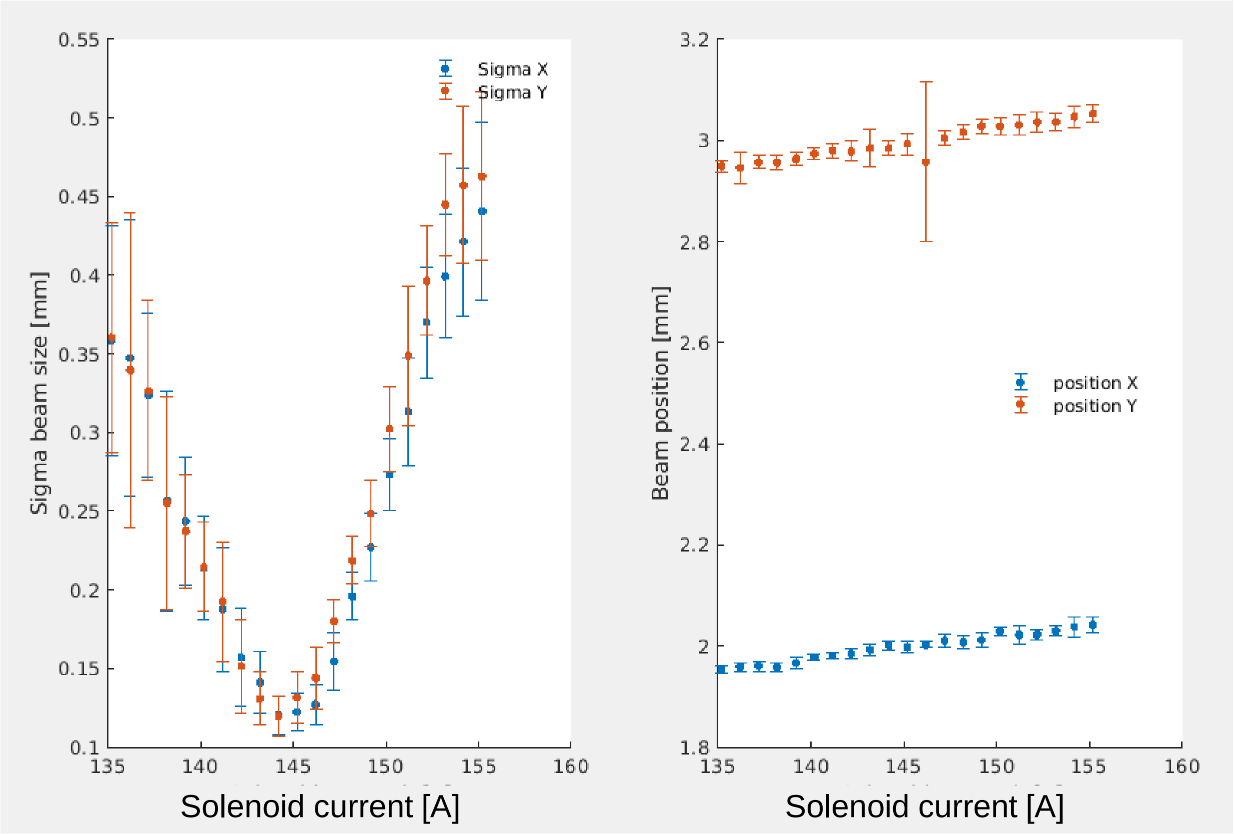
- **Method: scan the laser position on the cathode, and for each point, made a solenoid scan and determined the beam drift → select laser coordinates with smallest drift.**
- **Stable beam region accuracy set by drift distance of the laser spot within 160 μm.**



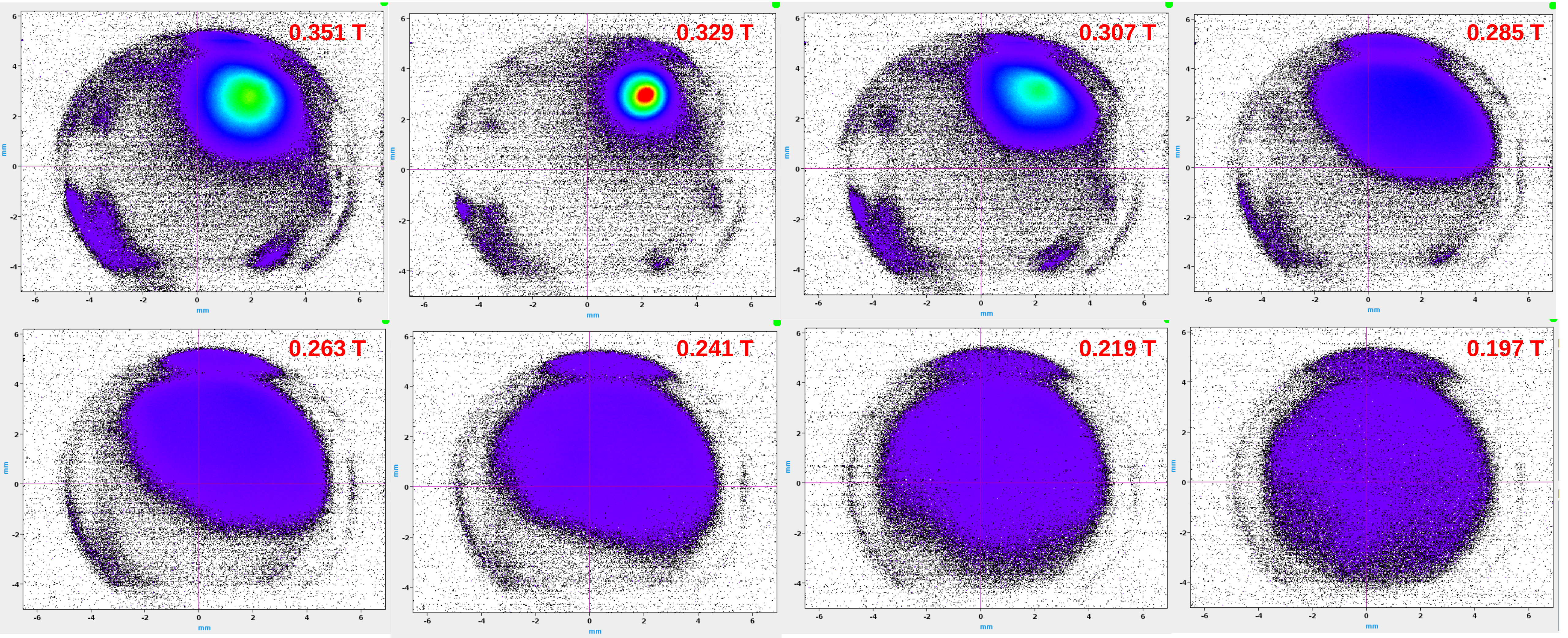
Alignment of laser spot on cathode with solenoid

Stable beam for a large range of solenoid strengths was obtained.





Stable beam point found

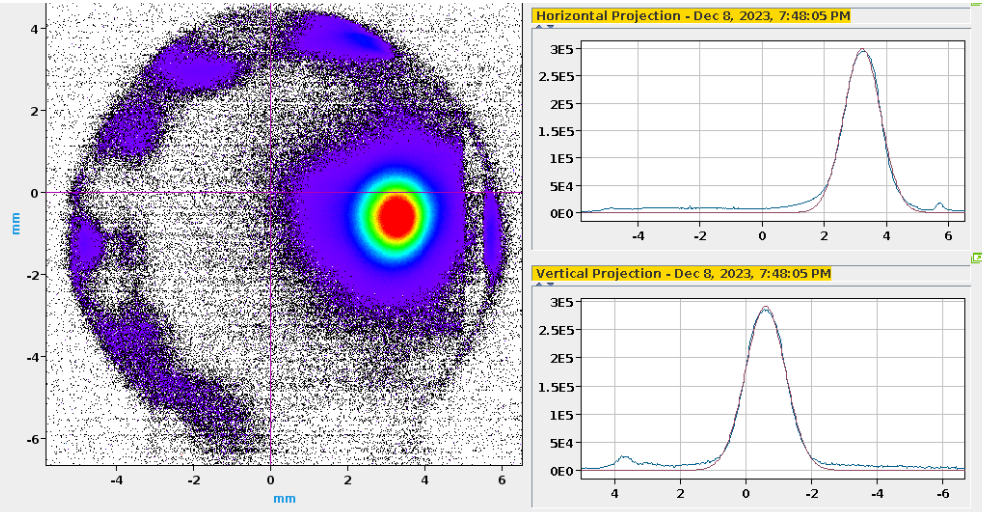


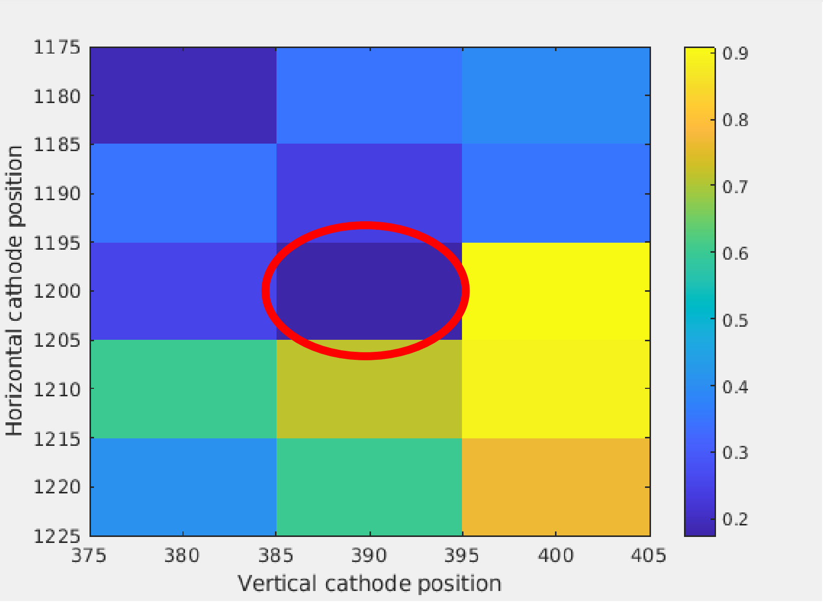
Centering the laser on cathode

- **Want to align the laser position on the cathode to be on-axis with the gun.**

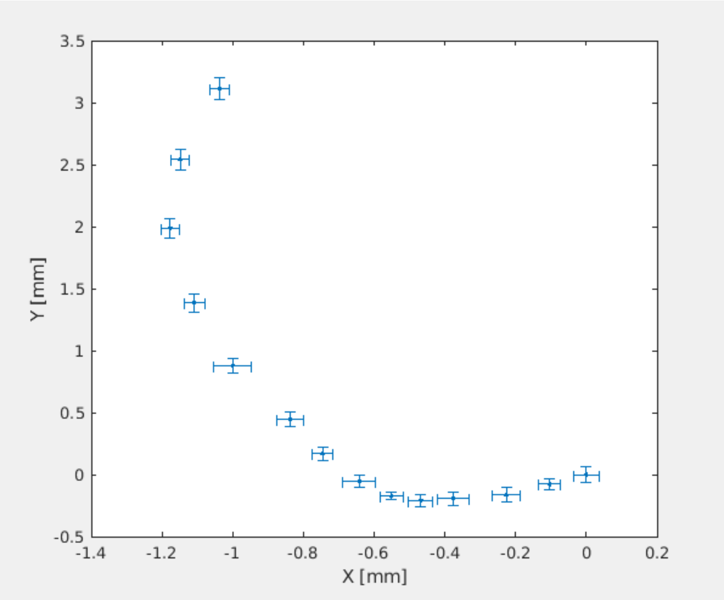
- **The RF was used to focus the electron beam with the solenoid turned off. To achieve this, used:**
  - low beam energy (1.5 MeV) → reduce dark current
  - low bunch charge (5 pC) → get small spot

- **A stability map of the laser position was made after setting a high RF phase (215 deg).**





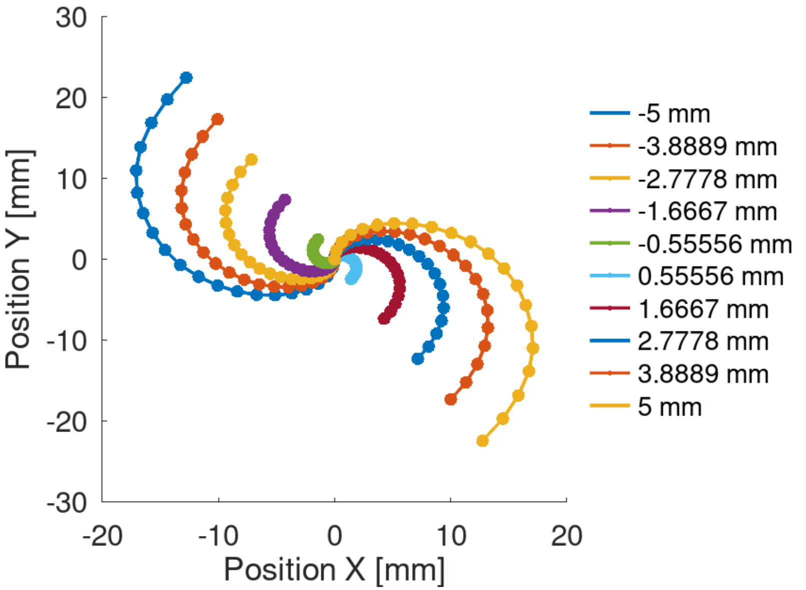
Centering the gun solenoid



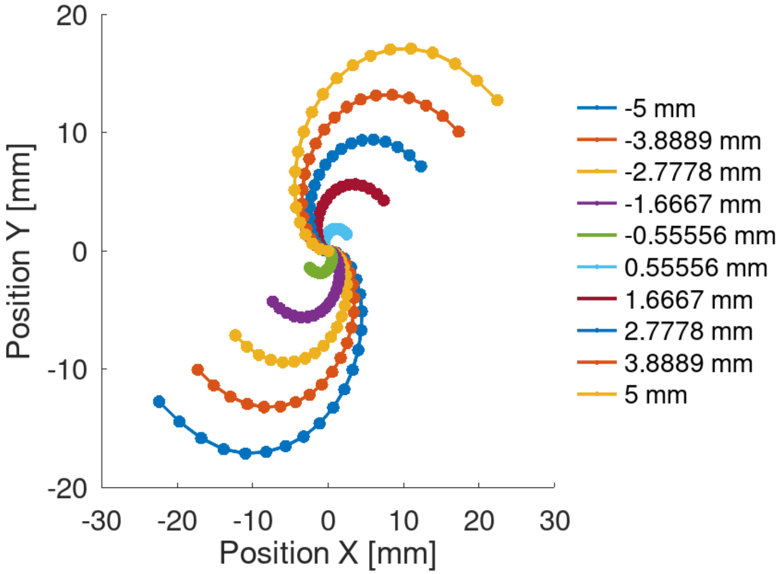
To further reduce the emittance from the gun, the position of the electron beam can be tracked through a solenoid scan

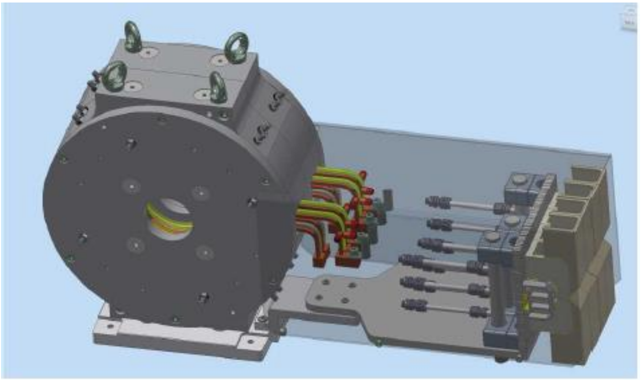
→ solenoid position and angle offset can be inferred by fitting the beam trajectory to simulations. Preliminary results predict a transverse misalignment less than 1 mm.

Solenoid X offset

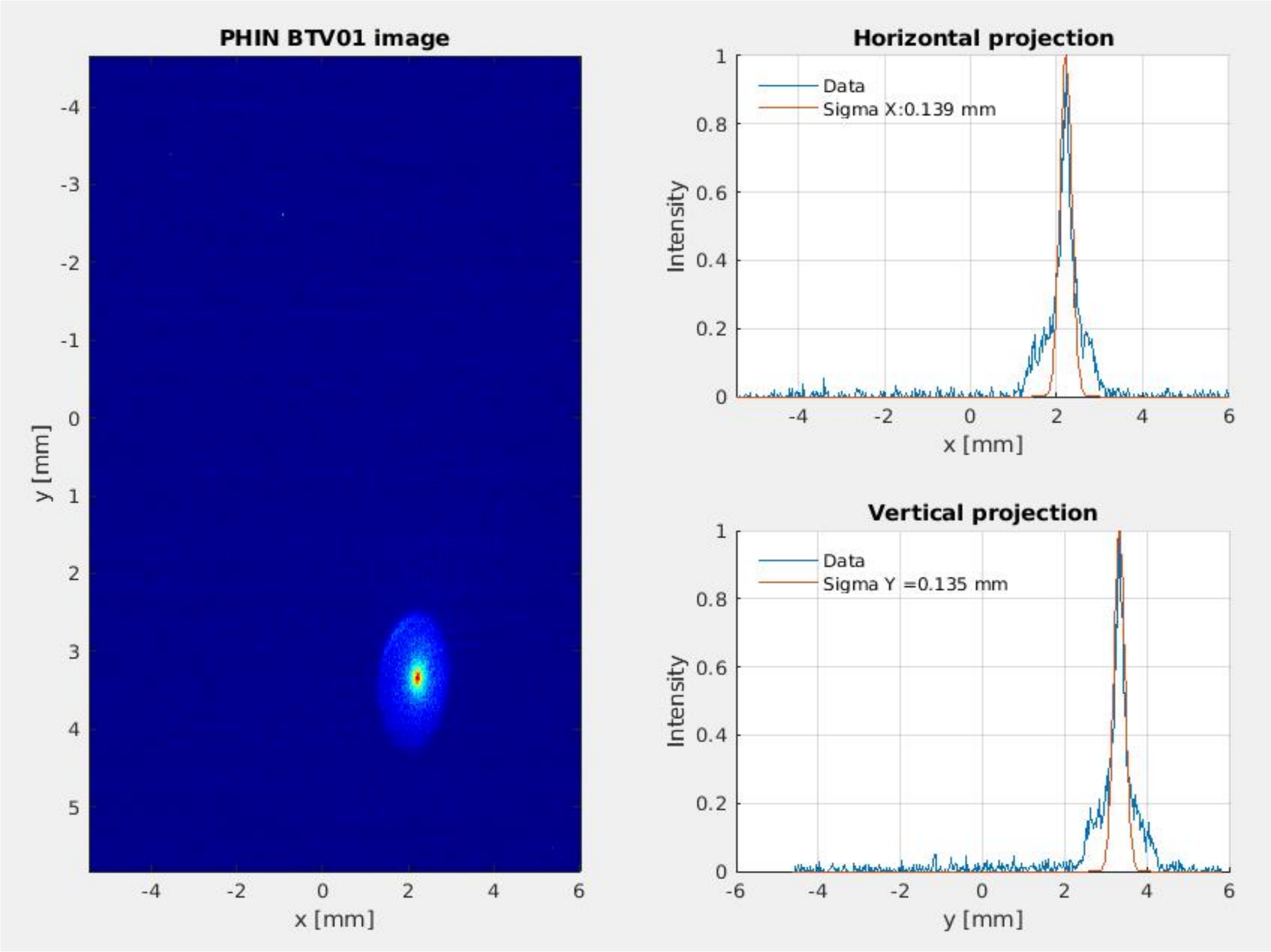


Solenoid Y offset





Small spot working point

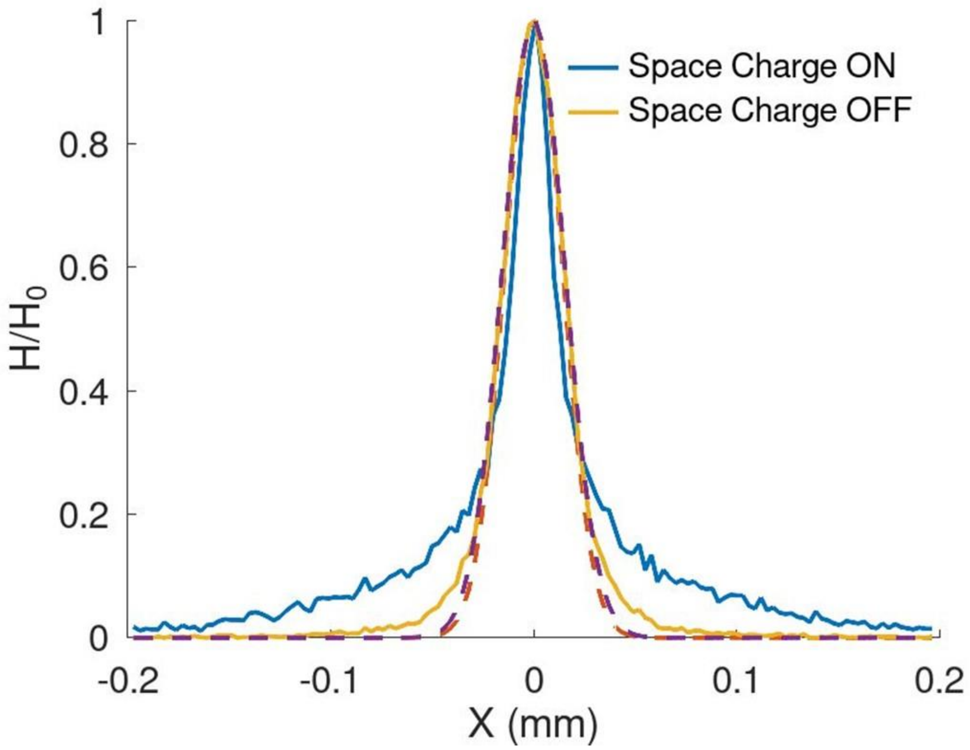


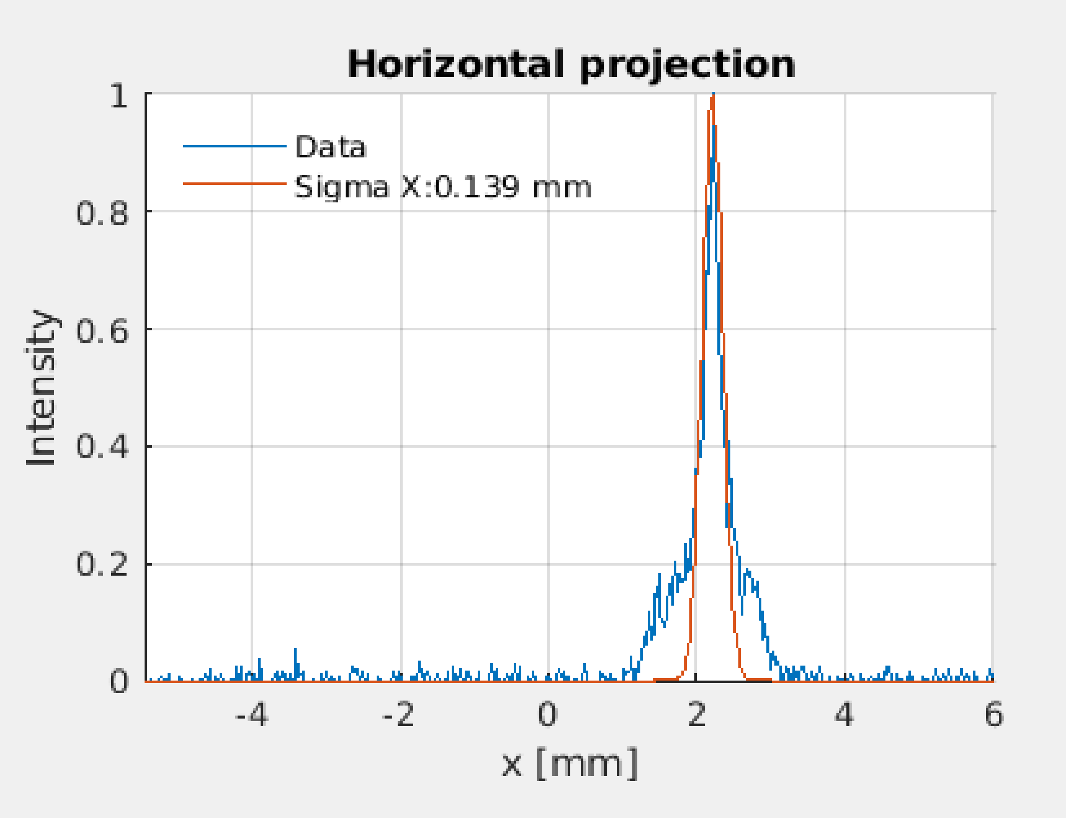
- Used a small RF phase and a laser RMS spot of 200 µm.
- An electron RMS spot of 100 µm was obtained for a bunch charge of 200 pC.
- At 400 pC, a 200 µm RMS spot was obtained.
- Note the presence of an electron beam halo, inducing a non-Gaussian beam profile.

Is this profile optimal for generating a high photon flux?

Optimum beam profile for high photon flux

Simulations indicate that non-Gaussian beam distributions with a sharp peak and space charge-induced halo achieve the highest flux.





Conclusions

- The CTF2 gun serves as an ideal test bench for an ICS proof of concept experiment.
- The obtainable X-ray parameters are compatible with water window microscopy.
- Working points have been defined to allow the generation of high flux photons.
- Installation and experiment to be completed during the first half of next year.
- End goal: experiment with a CLIC X-band structure-accelerated beam and Fabry-Perot cavity.
- Thanks to CTF2 team: Steffen Döbert, Edu Granados, Miguel Calderon.

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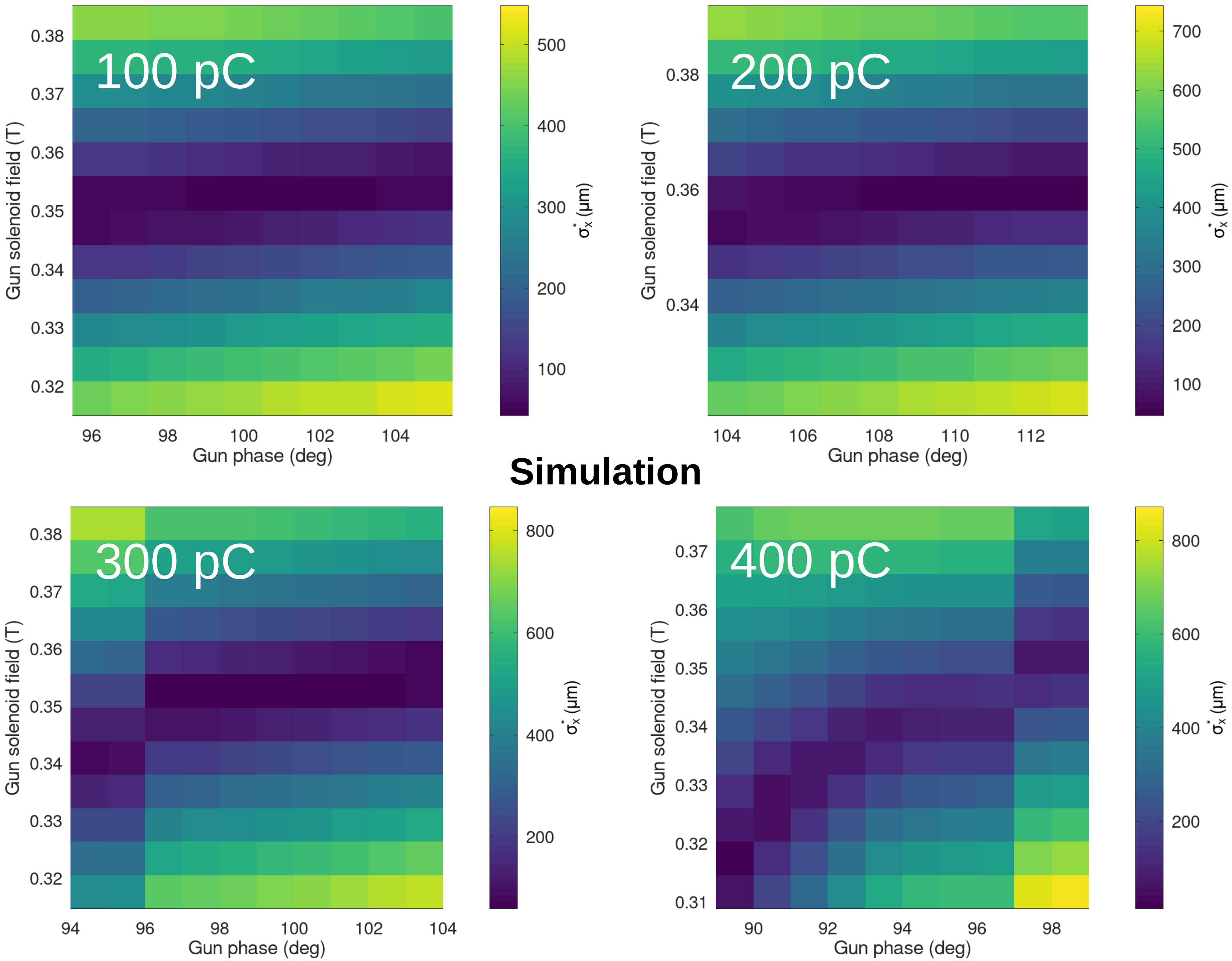
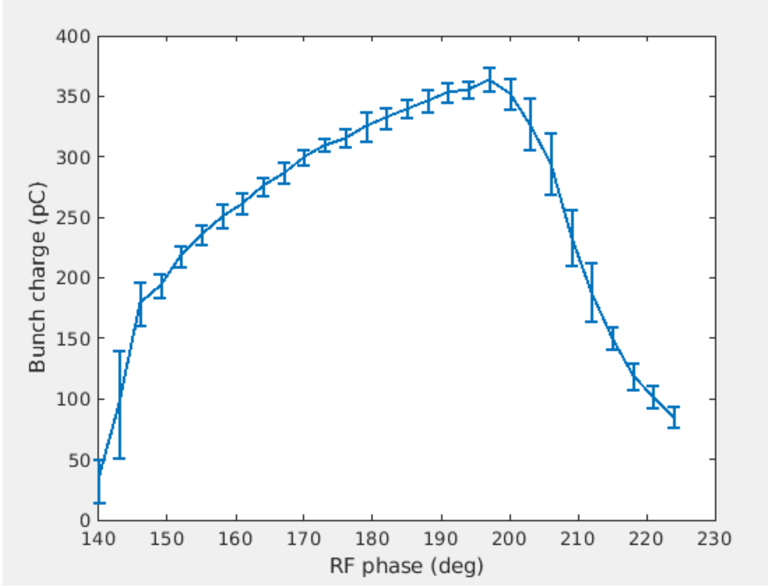
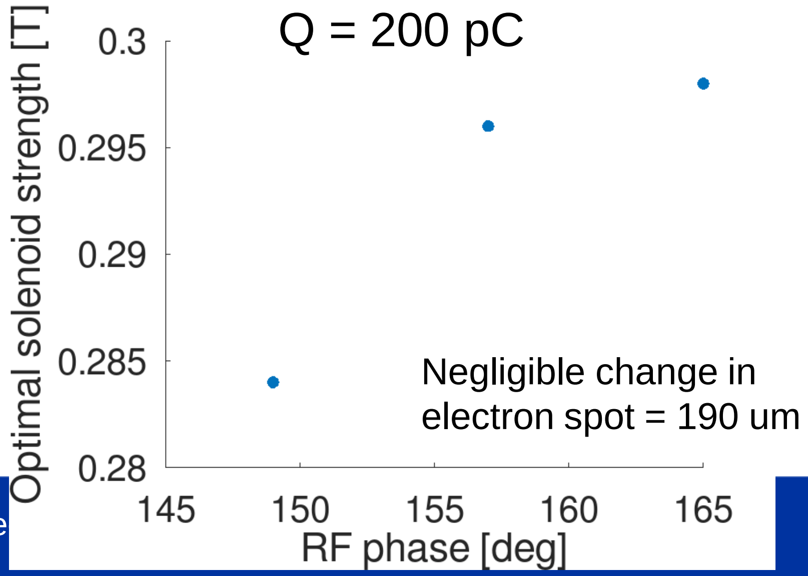
Impact of RF phase on electron spot size at IP

Simulation



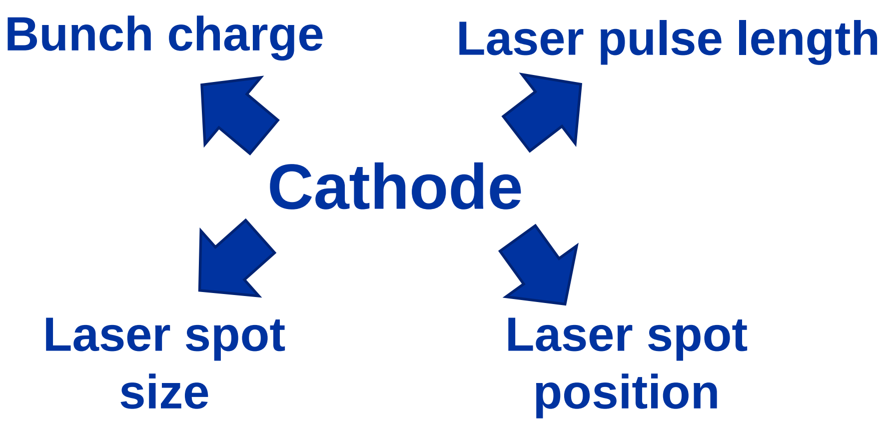
Measurement

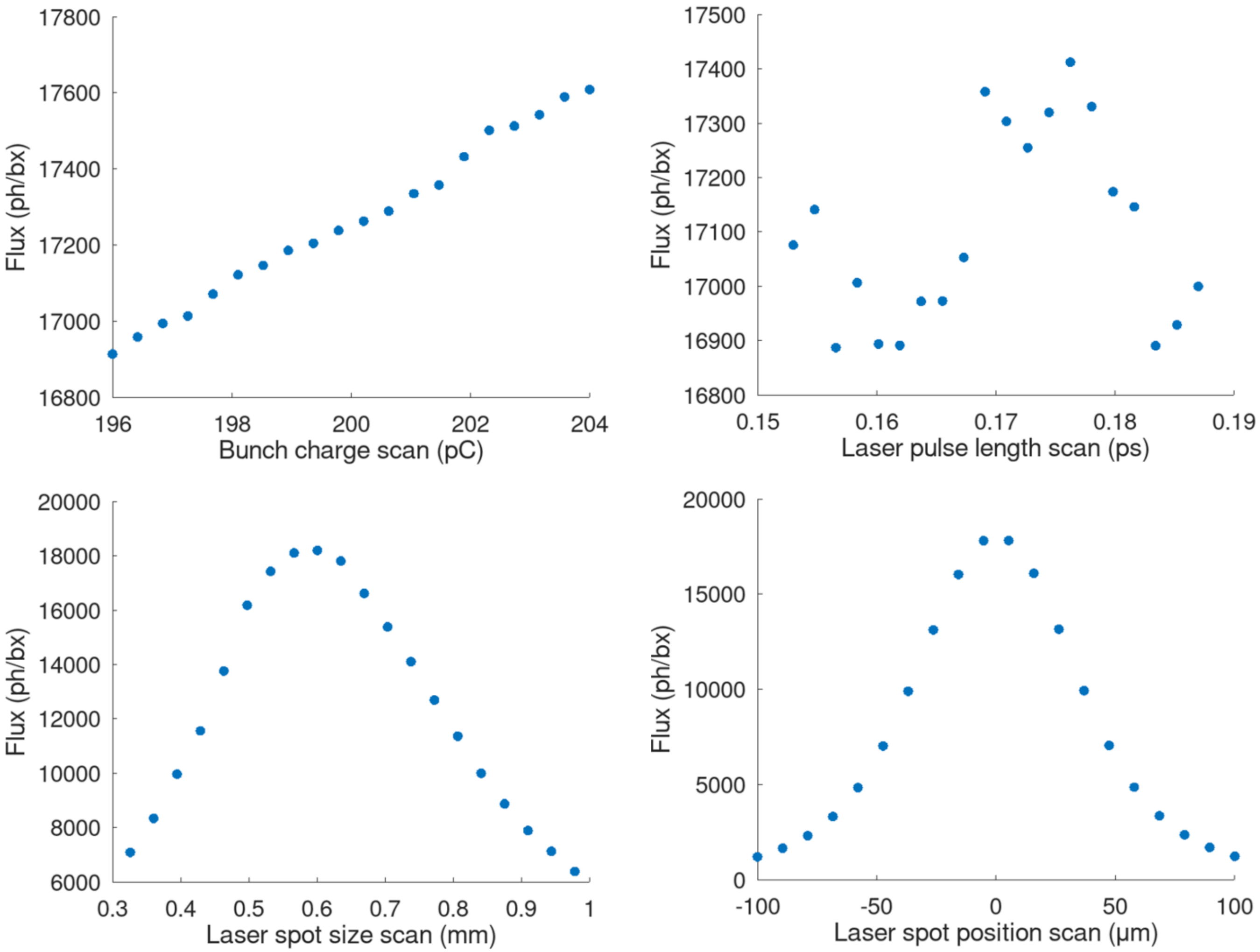




Tolerance study (Cathode)

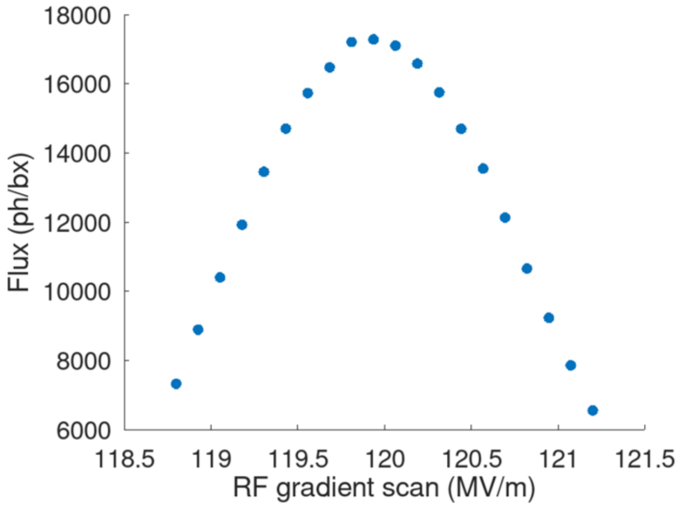
- **Determine the impact of offsets in injector parameters on the total flux from CBS.**
- **Tolerance study done for 200 pC with Copper cathode.**

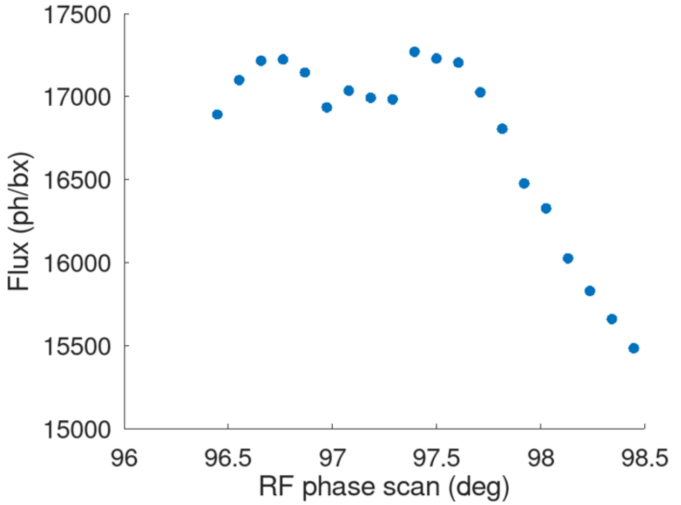




Tolerance study (RF Gun)

- **The RF gradient controls the beam energy at the injector exit.**
- **Difference with respect to nominal energy leads to poor focusing → flux is most sensitive to the gun gradient.**





RF Gun

Gradient **Phase**

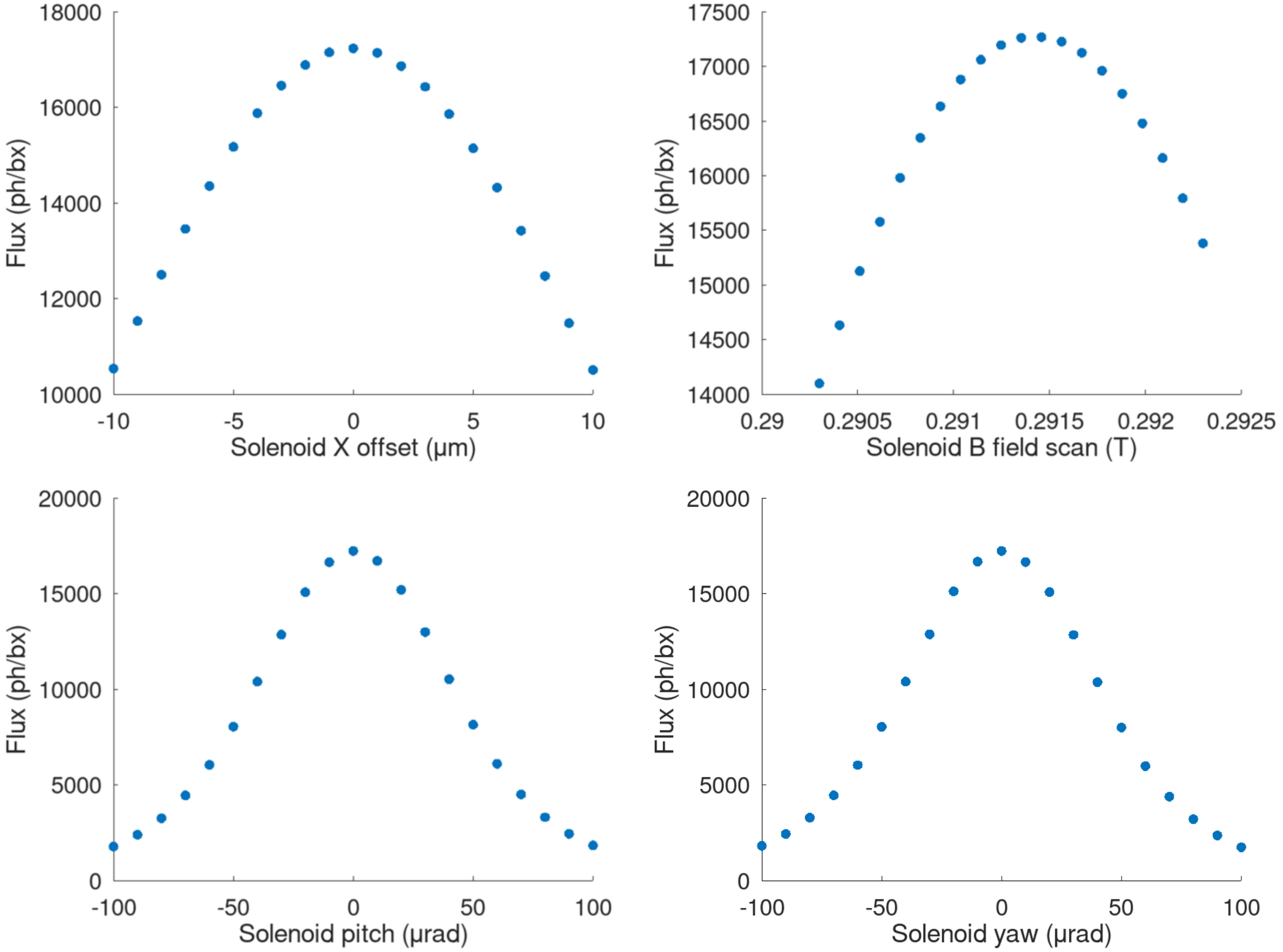
Tolerance study (Gun Solenoid)

- **Due to the strong focusing involved, the CBS photon flux is sensitive to offsets of the gun solenoid.**

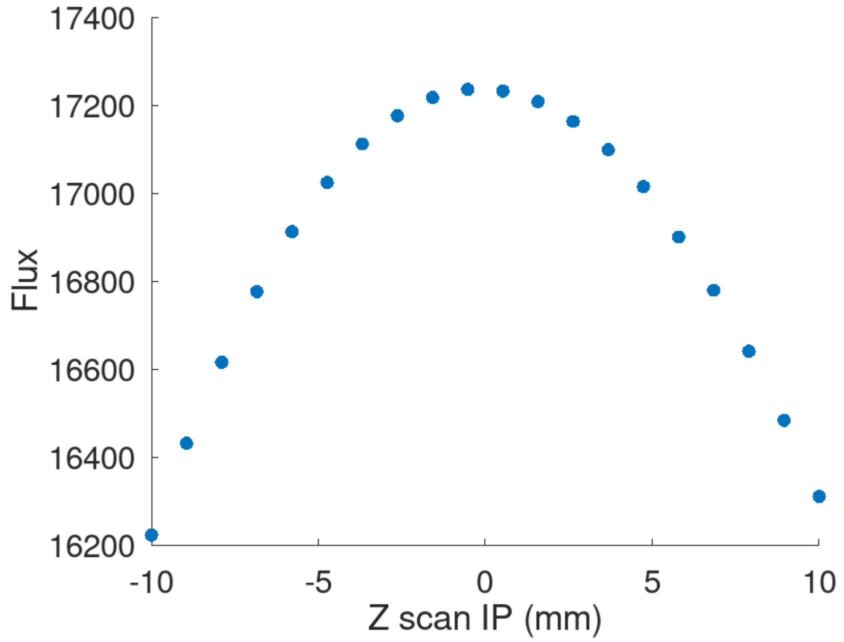
Solenoid

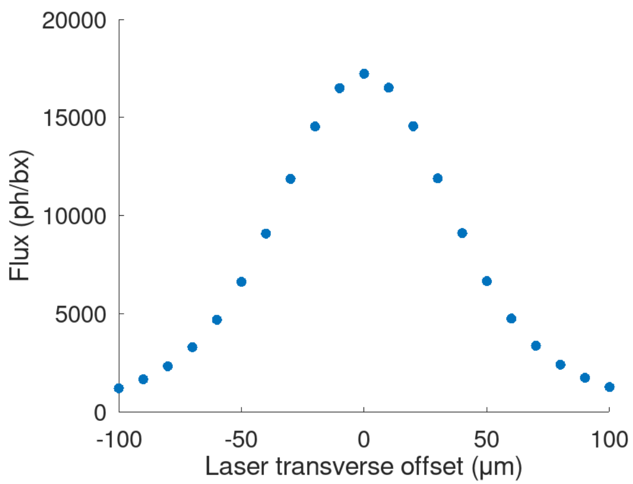
B-field amplitude

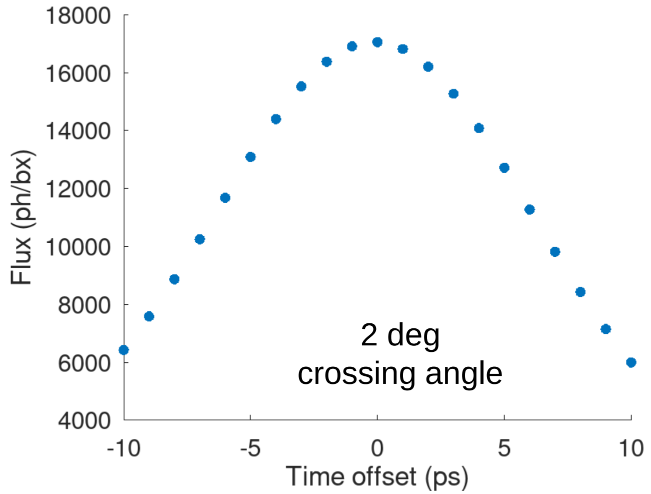
Offset Transverse & Angular



Tolerance study (IP region)







Electron beam phase space at the IP