First results for a compact ICS source based on the electron gun at CTF2

Vlad Musat, Andrea Latina

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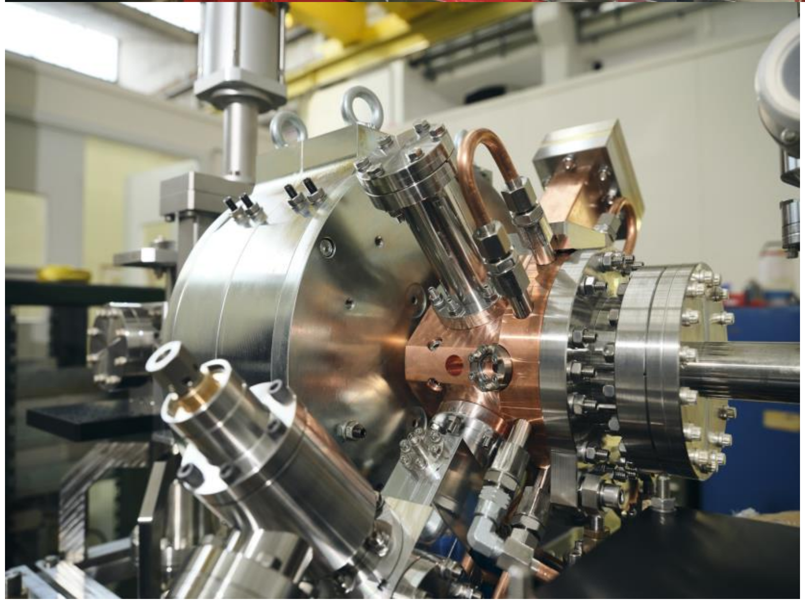
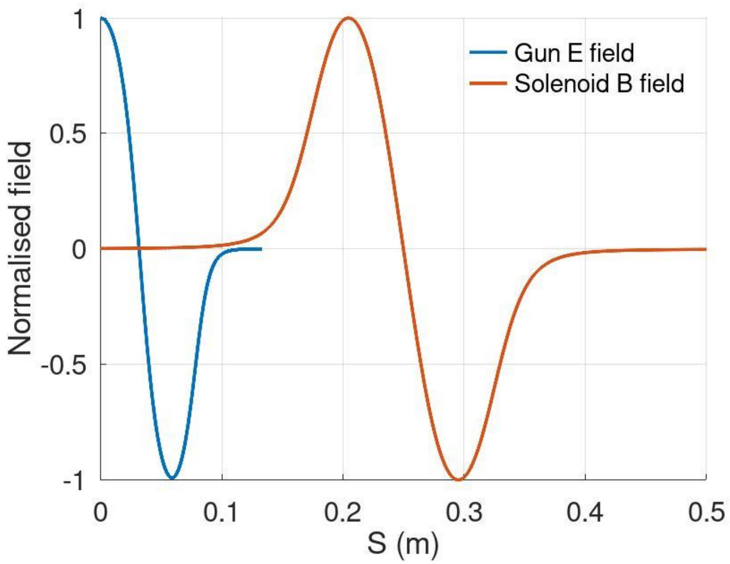
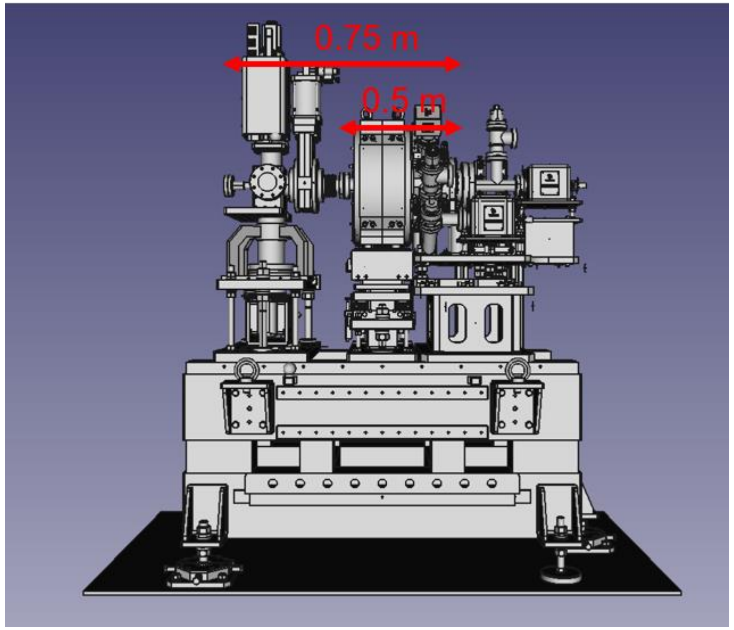
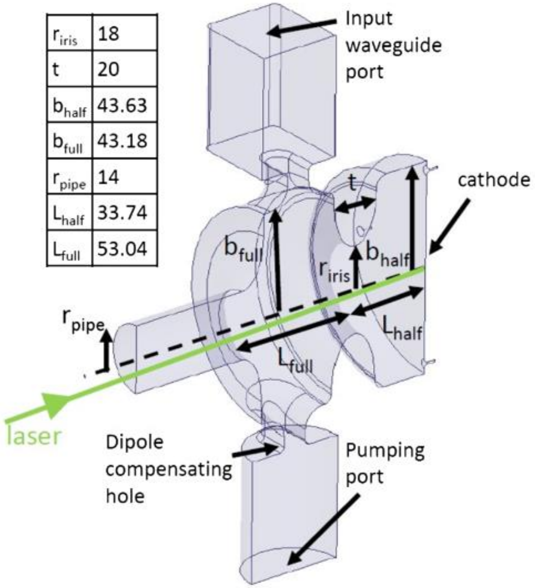


CTF2 gun



- 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].

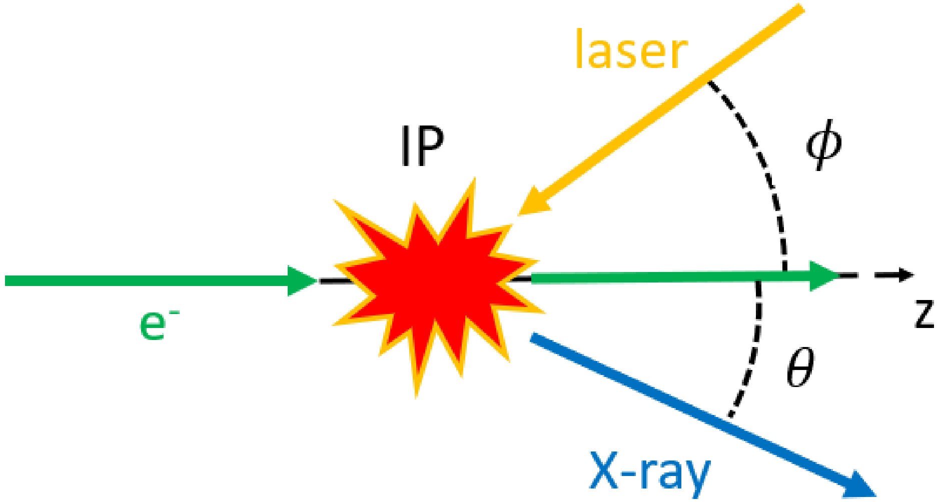




Gun parameter	Value
1.5 cell	S-band SW
F_{res} [GHz]	2.99855
Q_0	13,800
E_{acc} [MV/m]	120
Rep rate [Hz]	10
Working temperature	30 [°C]

[1] D. Alesini, et al. "Design, Realization, and High Power Test of High Gradient, High Repetition Rate Brazing-Free S-Band Photogun", Physical Review Accelerators and Beams, vol. 21, n. 11, November 2018

Inverse Compton scattering



= 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.

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

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

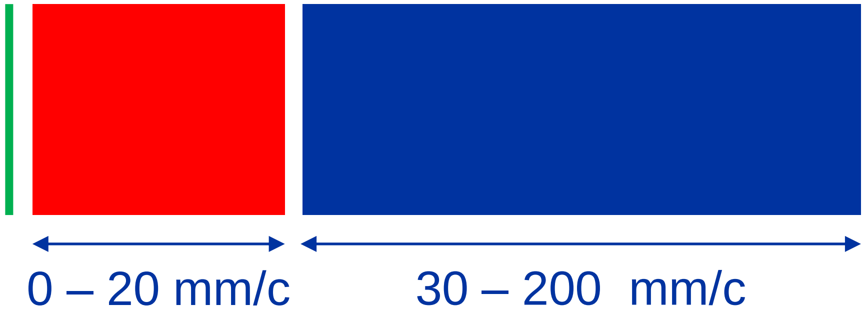
$$E_{\text{X-ray}} = 2\gamma^2 E_{\mathrm{laser}} \frac{1+\cos\phi}{1+\gamma^2\theta^2}$$

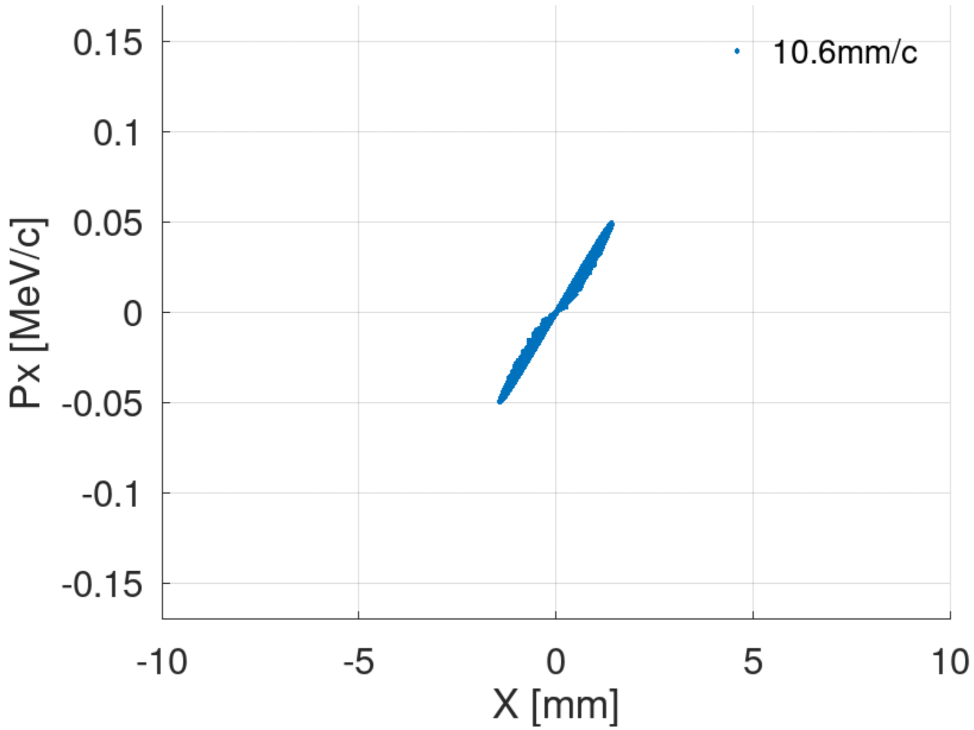
Photon energy

Optimisation of CTF2 injector for CBS experiment

- **A model of the CTF2 gun was implemented and optimised in RFT. The model comprised the cathode, gun, and solenoid.**

- **Optimisation goal: allow for the *maximum flux* at the gun exit and *minimal losses* in the beam pipe.**





Cathode	Gun	Solenoid
Bunch charge (laser intensity)	RF phase	Maximum B field
Laser spot size (Gaussian)		Distance from injector exit to IP

Beam focusing at the IP

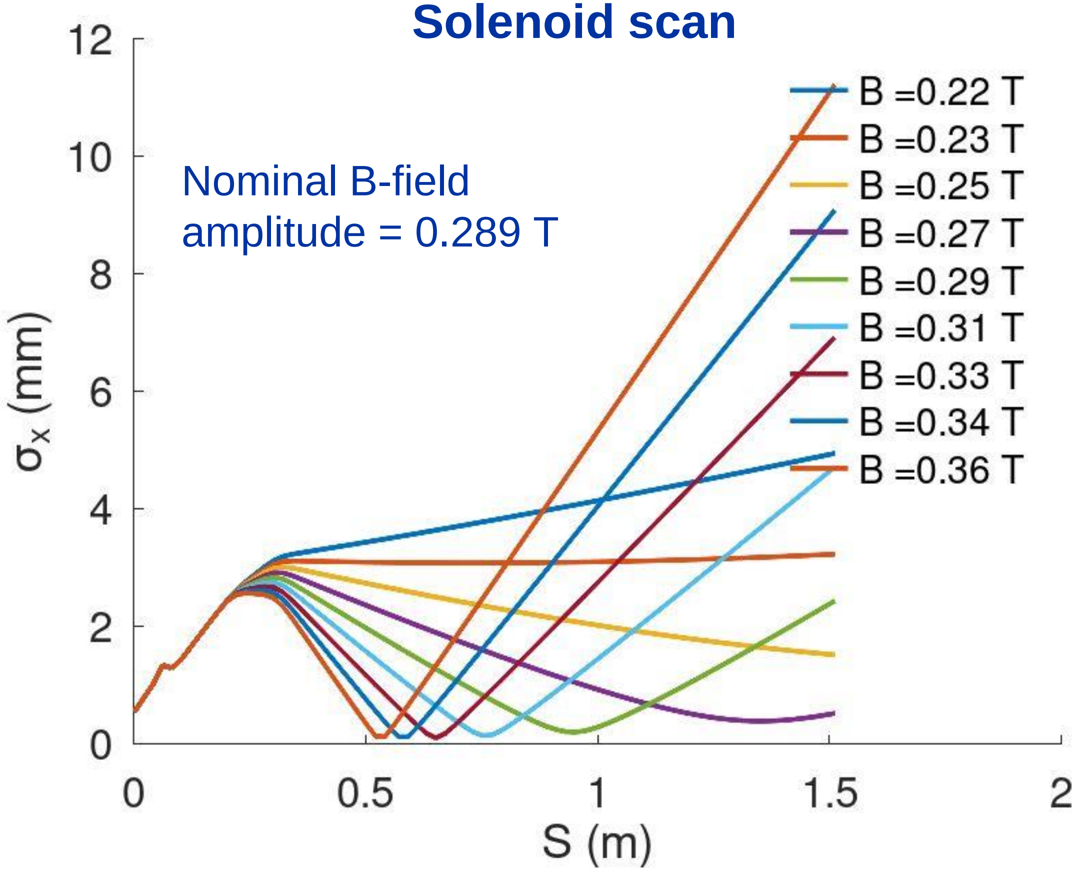
Options for focusing:

1. Quadrupoles ✗
2. Focusing solenoid ✗
3. Focusing solenoid + Quadrupoles ✗
4. Gun Solenoid ✓

Focusing with the gun solenoid:

- No other focusing required.
- Get the smallest beam size at the IP
- Optimum solution for electron beam under space charge effects.

Solenoid scan



Interaction set-up

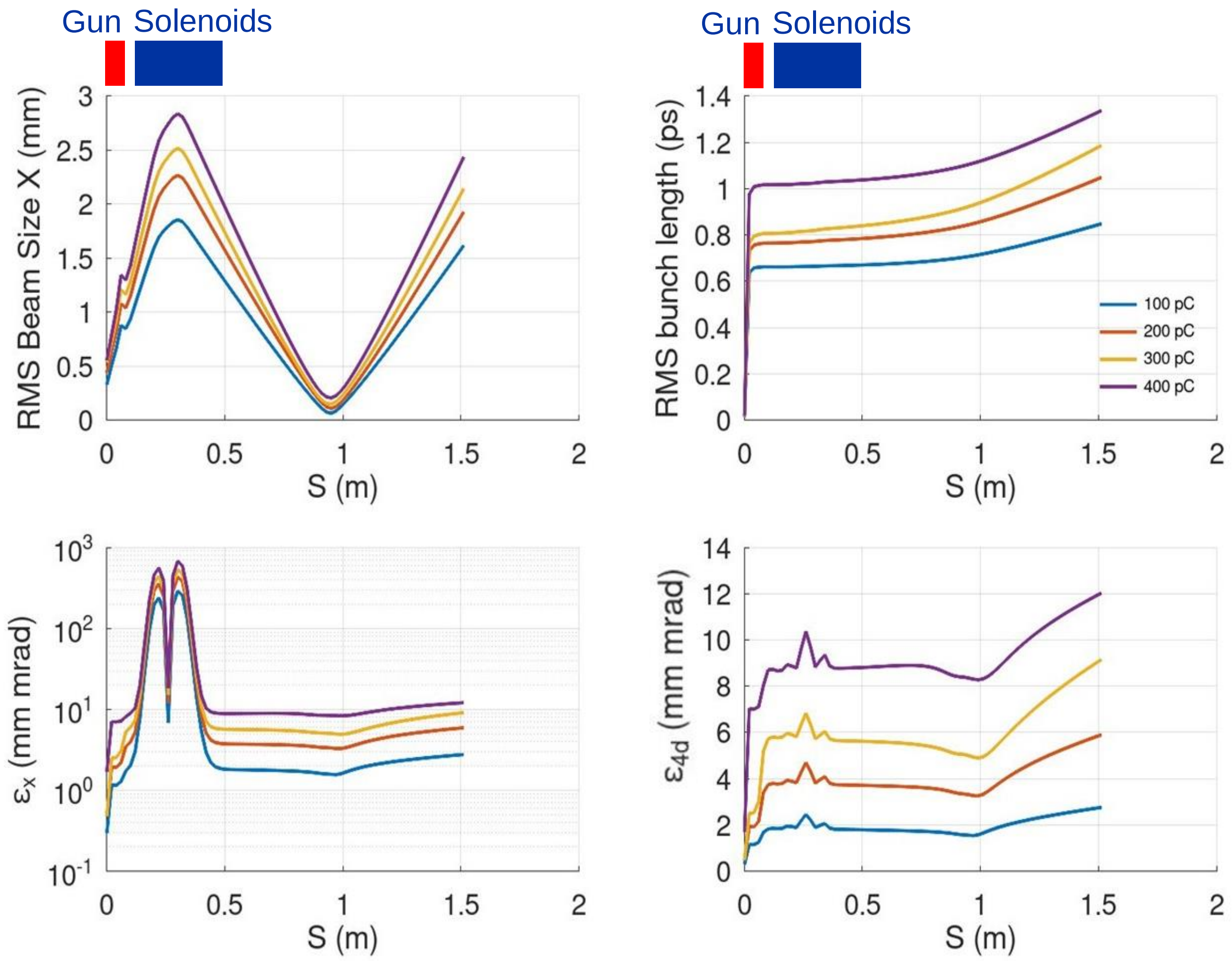
- **Cathode**
  - **Copper**
    - Single electron bunch — High intensity photon pulses, but no trains of bunches
    - Fed by PHAROS laser, split for interaction — 2 mJ single bunch laser good for Cu cathodes given low QE
  - **CsTe**
    - Multi-bunch electron beam — High intensity pulse trains → burst mode Fabry-Perot cavity R&D
    - Fed by PHIN laser, split for interaction — 10 μJ multi bunch laser (up to 100,000 pulses) good for multi-bunch electron trains

Set-up for Cu / CsTe cathodes

- Differences in the scattered photon parameters were mainly attributed to the lasers used for injection / interaction.
- Current set-up has a Copper cathode.
- PHAROS: large pulse energy & small pulse length → very good for single bunch interaction.
- PHIN can drive multi-bunch beams → comparable total flux (ph/s) for both Cu and CsTe
- PHIN can also be used to feed a Fabry-Perot cavity, to increase the total flux by 5 orders of magnitude.

Parameter	Copper	Cs_2Te
Injection laser	PHAROS	PHIN
IP laser	PHAROS	PHIN
Wavelength (on cathode)	1030 nm (257 nm)	1047 nm (262 nm)
Photon energy	4.824 eV	4.732 eV
Work function	4.7 eV	4.31 eV
Pulse energy	2 mJ	10 µJ
Burst energy (max)	2 mJ	1 J
Pulse length	0.17 ps	4 ps
Quantum efficiency	$\sim 9 \times 10^{-4}$	~ 0.1

Evolution of beam parameters with Cu cathode



Setup	Unit	100 pC	200 pC	300 pC	400 pC
Gun phase (RFT)	Deg	93.47	93.96	93.96	93.59
Gun gradient	MV/m	120	120	120	120
Max B field	T	0.2899	0.2895	0.2896	0.2892
Laser RMS size	mm	0.483	0.615	0.879	0.553
Distance cathode to IP	m	0.936	0.939	0.933	0.937

Parameter at IP	Unit	100 pC	200 pC	300 pC	400 pC
Beam energy	MeV	5.728	5.733	5.723	5.722
ϵ_x^n	mm mrad	1.57	3.32	5.03	8.38
$\sigma_{el,\,max}$	mm	1.86	2.27	2.52	2.84
$\sigma^*_{x,el}$	µm	60	105	142	202
$\sigma^*_{z,el}$	ps	0.70	0.84	0.92	1.10
Photons per bunch	Ph/bx	**13,000**	**16,000**	**15,000**	**18,000**
Total flux	Ph/s	**130,000**	**160,000**	**150,000**	**180,000**

Rep rate = 10 Hz

Evolution of beam parameters with Cu cathode

High number of photons generated per bunch.

But

1. **PHAROS injection allows for single bunch operation only.**
2. **Set limit on flux.**
3. **Consider the placement of a CsTe cathode.**

Setup	Unit	100 pC	200 pC	300 pC	400 pC
Gun phase (RFT)	Deg	93.47	93.96	93.96	93.59
Gun gradient	MV/m	120	120	120	120
Max B field	T	0.2899	0.2895	0.2896	0.2892
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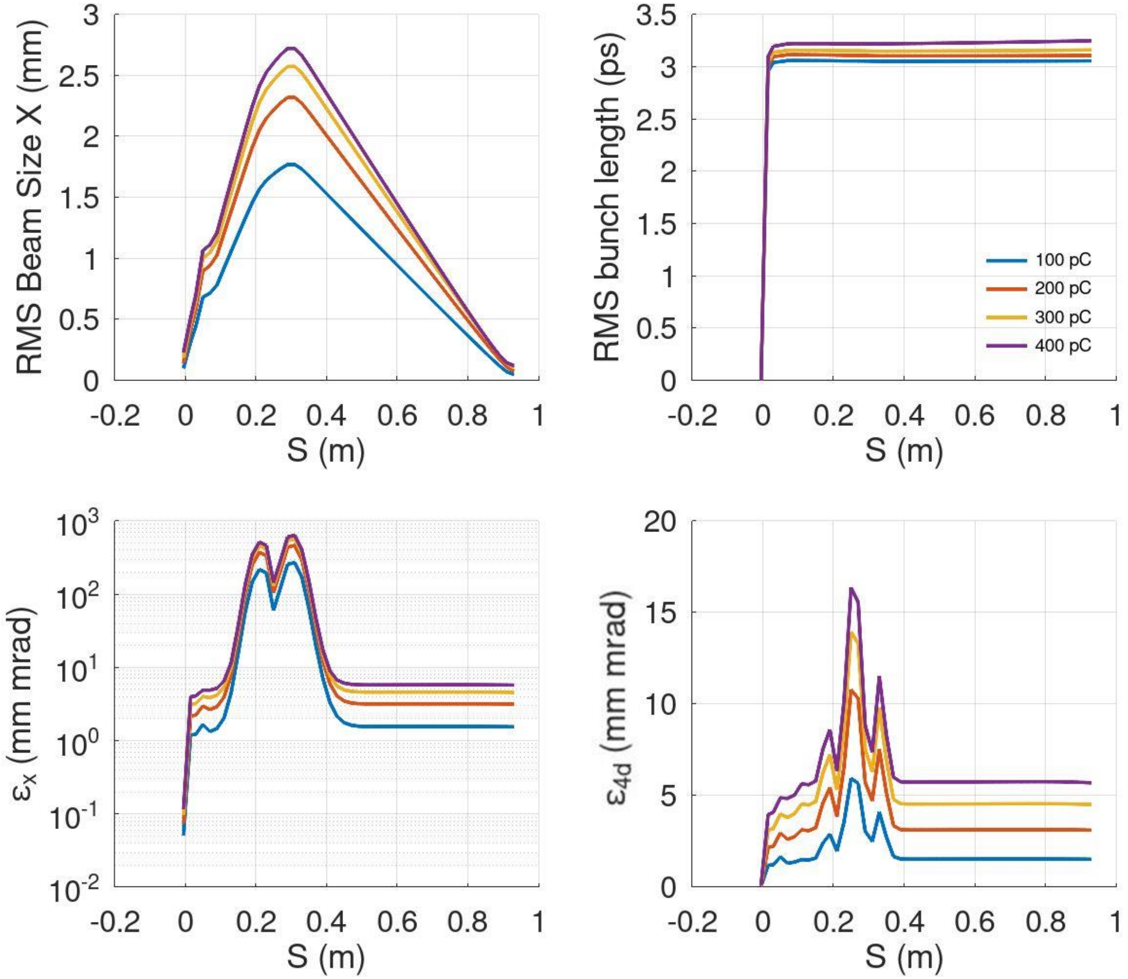
Rep rate = 10 Hz

Evolution of beam parameters with Cs_2Te cathode



Setup	Unit	100 pC	200 pC	300 pC	400 pC
Gun phase (RFT)	Deg	120.00	119.00	118.89	119.85
Gun gradient	MV/m	120	120	120	120
Max B field	T	0.3035	0.3028	0.3023	0.3027
Laser RMS size	mm	0.100	0.143	0.189	0.229
Distance cathode to IP	m	0.920	0.923	0.926	0.922

Parameter at IP	Unit	100 pC	200 pC	300 pC	400 pC
Beam energy	MeV	5.90	5.90	5.90	5.90
ϵ_x^n	mm mrad	1.55	3.14	4.55	5.75
$\sigma_{el,\,max}$	mm	1.77	2.32	2.57	2.72
$\sigma^*_{x,el}$	µm	48.5	76.0	100	121
$\sigma^*_{z,el}$	ps	3.06	3.12	3.17	3.26
Photons per bunch	Ph/bx	**158**	**191**	**210**	**235**
Total flux	Ph/s	**126,400**	**152,800**	**168,000**	**188,000**

Rep rate = 10 Hz × 80 bunches/train

Evolution of beam parameters with Cs_2Te cathode

Small number of photons scattered per bunch.

But

1. **CsTe cathode allows for multi-bunch operation.**
2. **Over 1e5 further increase in flux by installing a burst-mode operated Fabry-Perot cavity.**
3. **Would constitute the first test of flux enhancement with a burst mode FPC in a linac-based source.**
4. **Great potential for R&D in linac-based CBS sources.**

Setup	Unit	100 pC	200 pC	300 pC	400 pC
Gun phase (RFT)	Deg	120.00	119.00	118.89	119.85
Gun gradient	MV/m	120	120	120	120
Max B field	T	0.3035	0.3028	0.3023	0.3027
Laser RMS size	mm	0.100	0.143	0.189	0.229
Distance cathode to IP	m	0.920	0.923	0.926	0.922

Parameter at IP	Unit	100 pC	200 pC	300 pC	400 pC
Beam energy	MeV	5.90	5.90	5.90	5.90
ϵ_x^n	mm mrad	1.55	3.14	4.55	5.75
$\sigma_{el,\,max}$	mm	1.77	2.32	2.57	2.72
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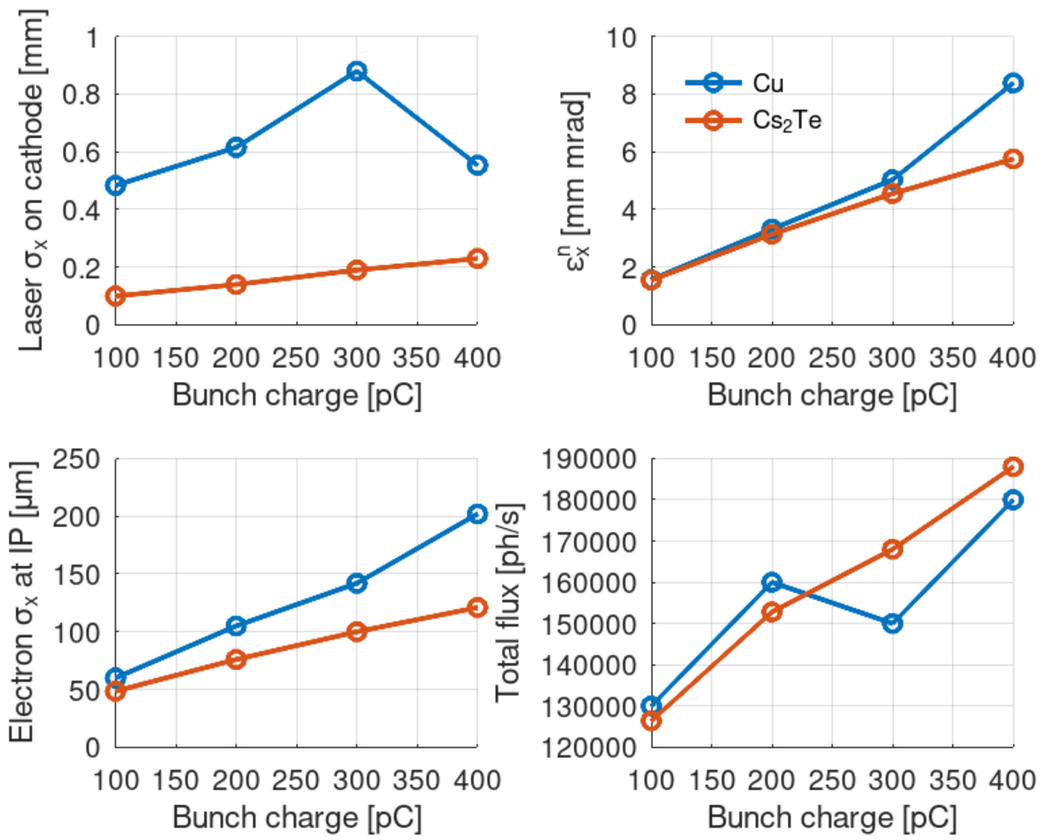
Rep rate = 10 Hz × 80 bunches/train

CTF2: Copper vs Cs_2Te

Parameter	Unit	CTF2 + PHAROS + Copper	CTF2 + Cs_2Te + PHIN
		Single bunch	**Multi-bunch**
Compton edge	keV	0.57	0.63
X-ray pulse duration	ps	0.7	5
Ph/bunch		2×10^4	2×10^2
Bunches		1	80
Total flux	ph/s	$\mathbf{1.8 \times 10^5}$	$\mathbf{1.9 \times 10^5}$

Parameter	Unit	CTF2 + PHIN + Cs_2Te + FPC
Bunches/train		80
Max Effective gain		60
Max Effective energy	J	0.5
Total flux	ph/s	$\mathbf{9.5 \times 10^9}$



CTF2: Copper vs Cs_2Te

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Compton edge	keV	0.57	0.63
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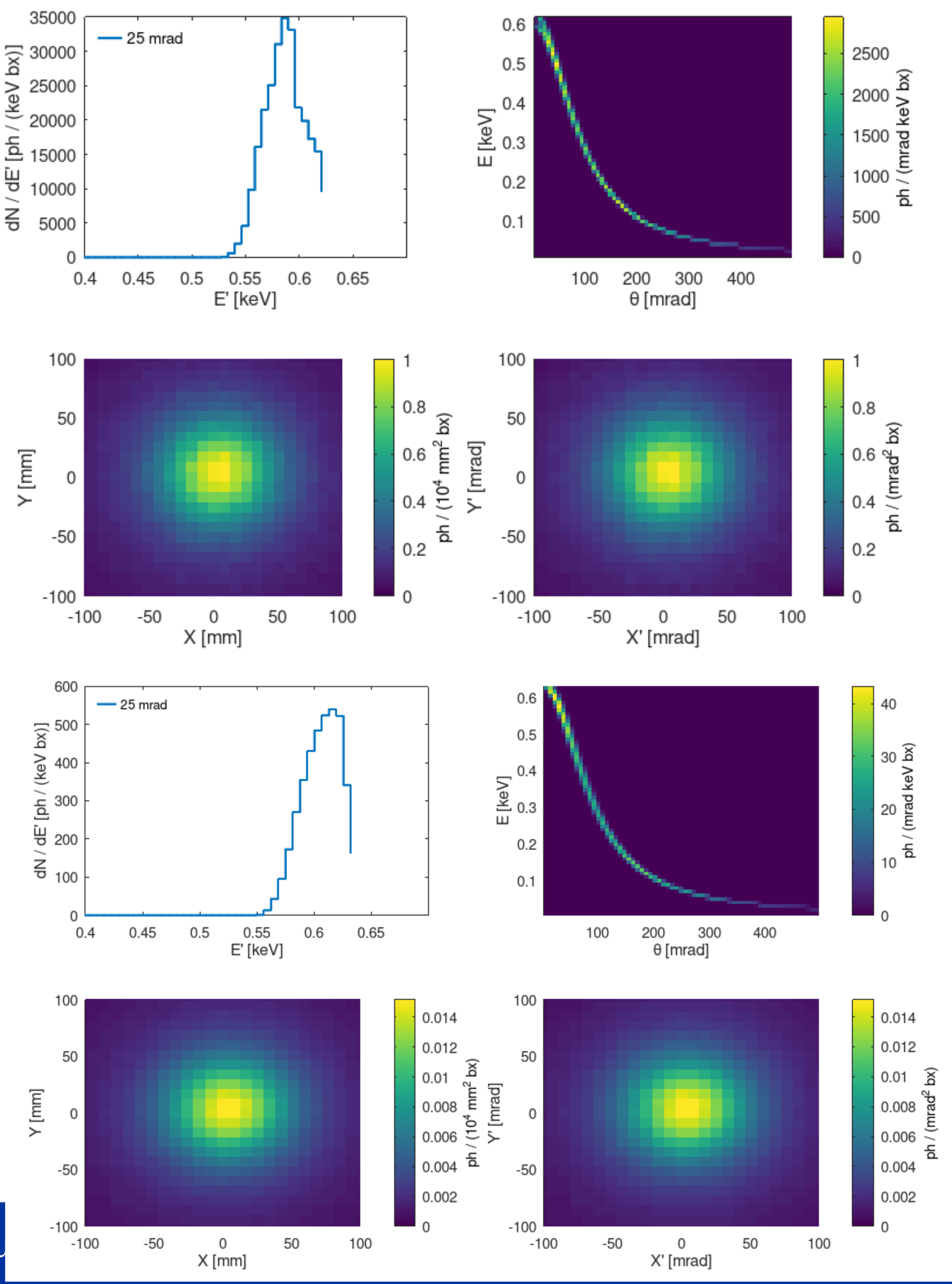
Parameter	Unit	CTF2 + PHIN + Cs_2Te + FPC
Bunches/train		80
Max Effective gain		60
Max Effective energy	J	0.5
Total flux	ph/s	$\mathbf{9.5 \times 10^9}$

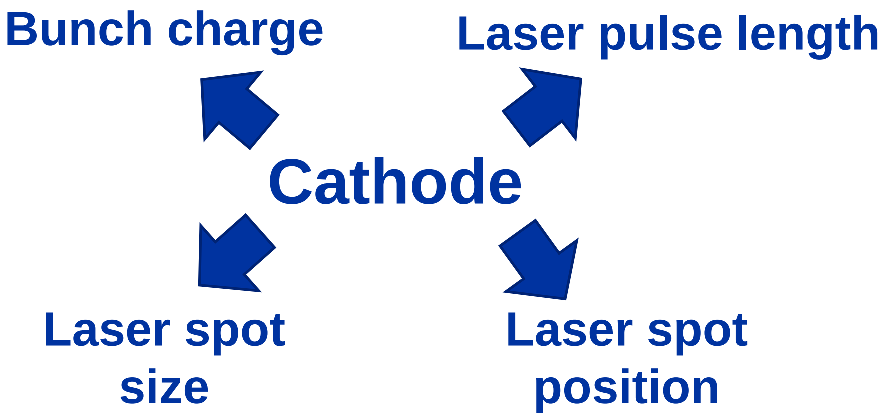


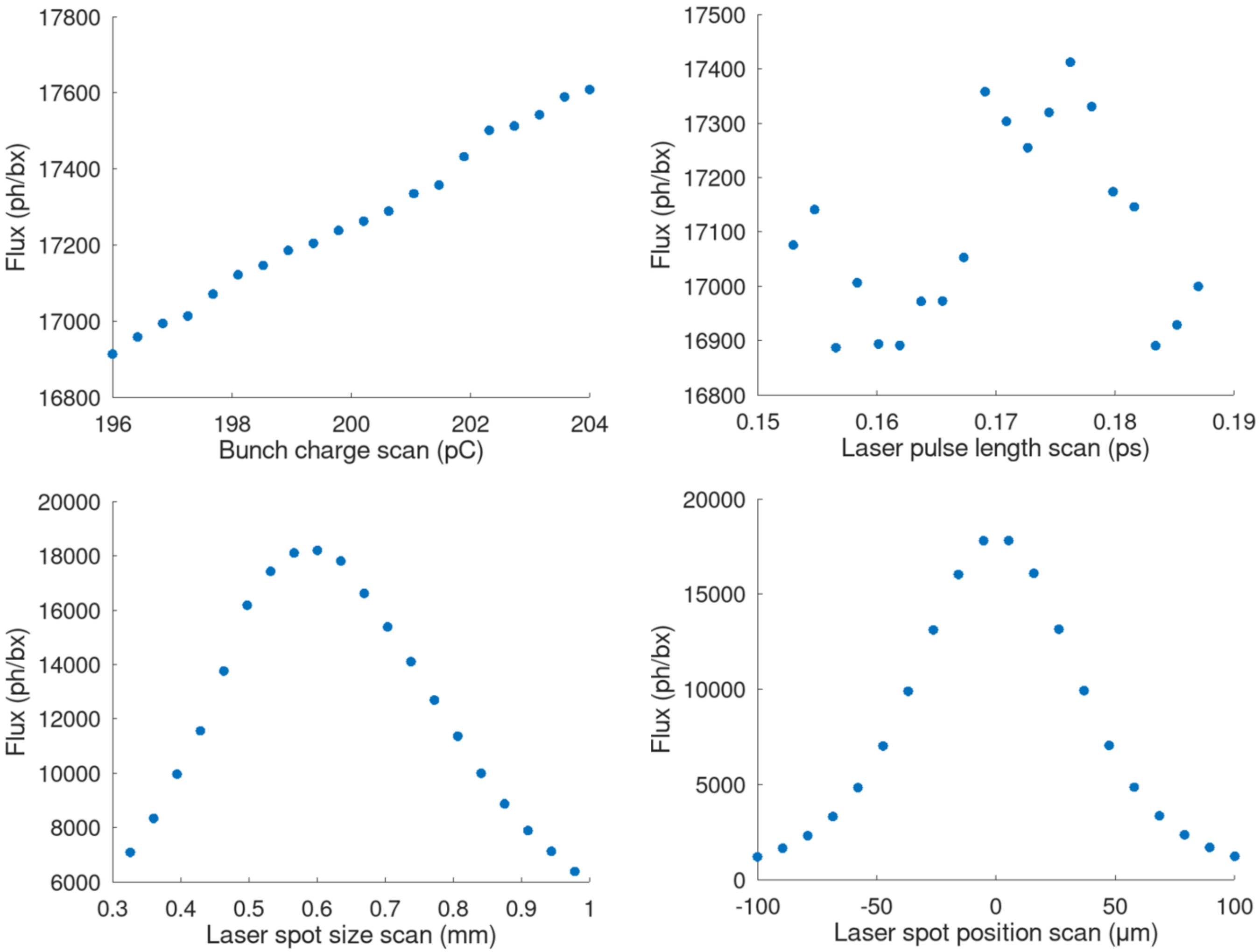
Copper

Cs_2Te

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.



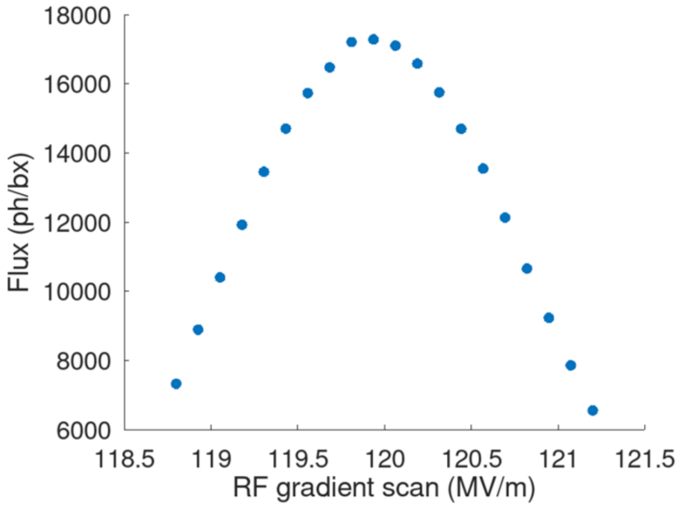


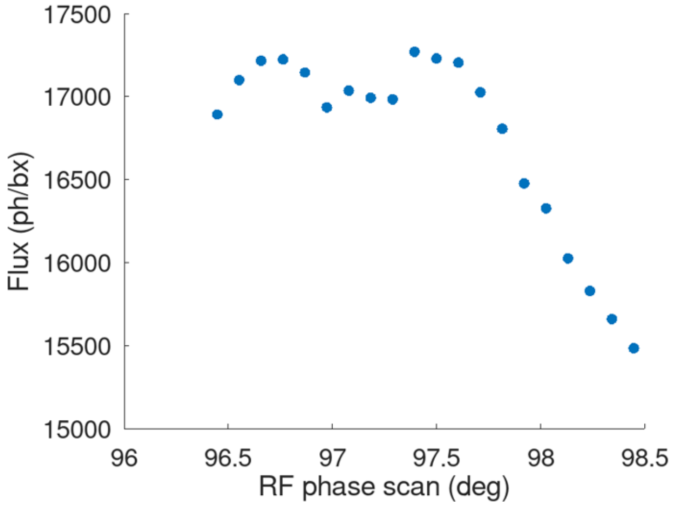
Tolerance study (RF Gun)

- 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**





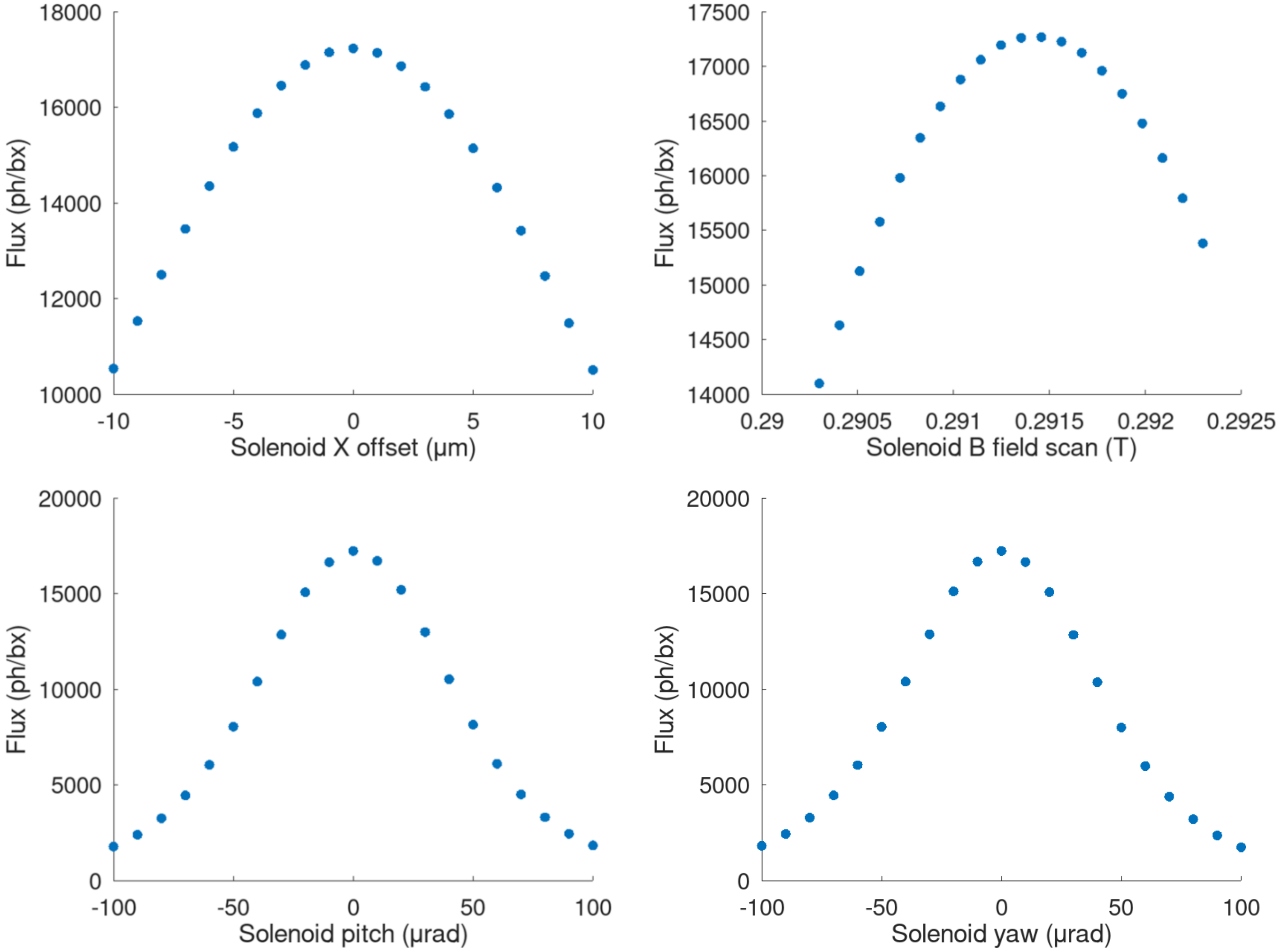
Tolerance study (Gun Solenoid)

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

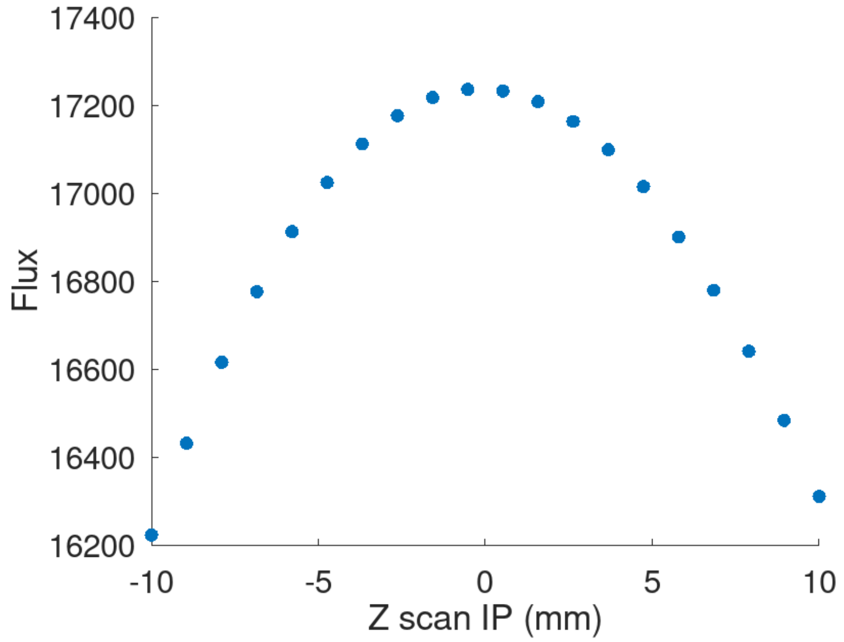
Solenoid

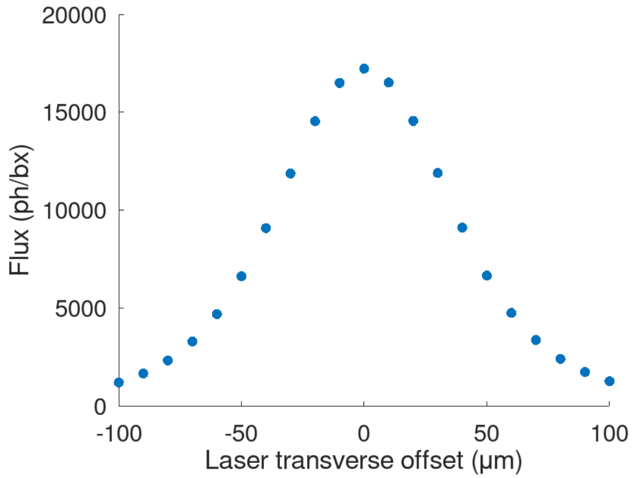
B-field amplitude

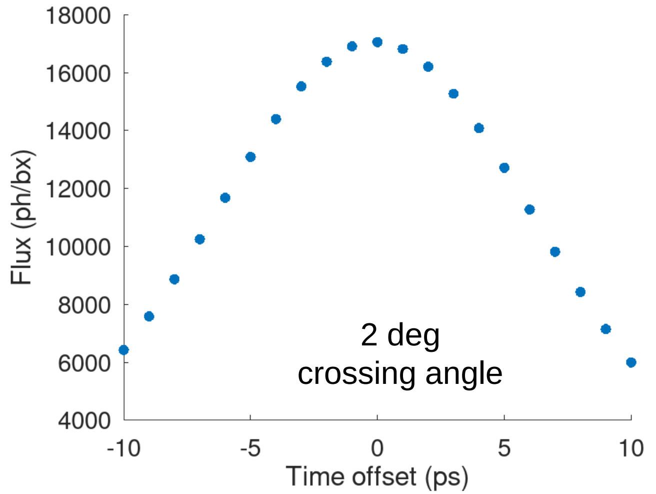
Offset Transverse & Angular



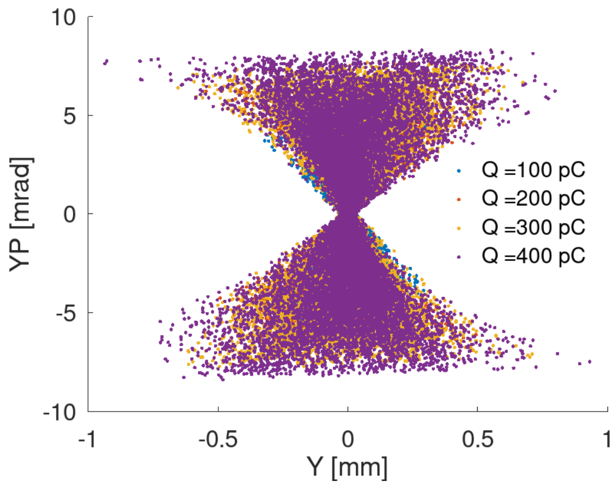
Tolerance study (IP region)

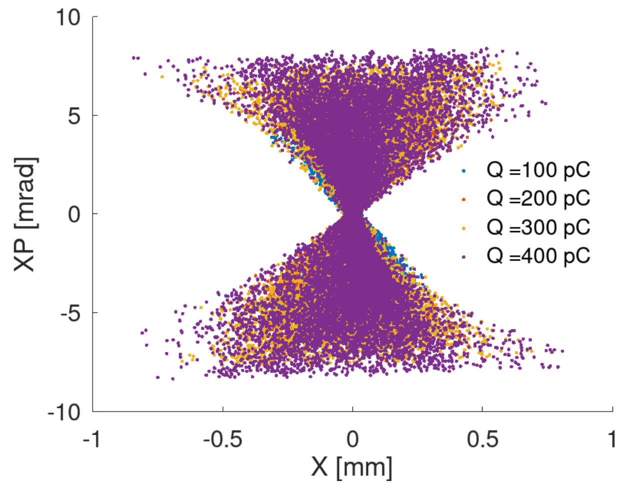






Electron beam phase space at the IP





Tolerance study CTF2 (Copper, 200 pC)

Tolerance parameter	Tolerance Cu (200 pC)	Tolerance Cs_2Te (400 pC)
Cathode		
Bunch charge	30 pC	Negligible
Laser pulse length	Negligible ($\pm 10\%$)	Negligible
Laser spot size	90 µm (15% σ_x)	62 µm (27% σ_x)
Laser spot position	20 µm (3.3% σ_x)	26 µm (11.3% σ_x)
RF gun		
RF gradient	0.3 MV/m (0.25%)	[+ 0.6 / - 0.4] MV/m (0.4%)
RF phase	1°	10.6°
Gun solenoid		
Max solenoid field	0.9 mT (3‰)	2.8 mT (9‰)
XY solenoid offset	6 µm	8 µm
Pitch solenoid offset	20 µrad	30 µrad
Yaw solenoid offset	20 µrad	30 µrad
IP region		
Z scan around IP	30 mm	20 mm
Interaction time	4.5 ps	6 ps
Laser transverse offset	23 µm (92% σ^*_{laser})	20 µm (80% σ^*_{laser})

Most significant tolerances:

1. RF gradient
2. Max solenoid B field
3. Solenoid offset

- Laser transverse offset is dependent on the laser sigma spot size at the IP (set to 25 μm).
- Tolerance was computed with respect to a 20% loss in flux.
- The interaction time scan was performed given a crossing angle of 2°

Least significant tolerances:

1. Laser pulse length
2. RF phase
3. Bunch charge

Conclusions

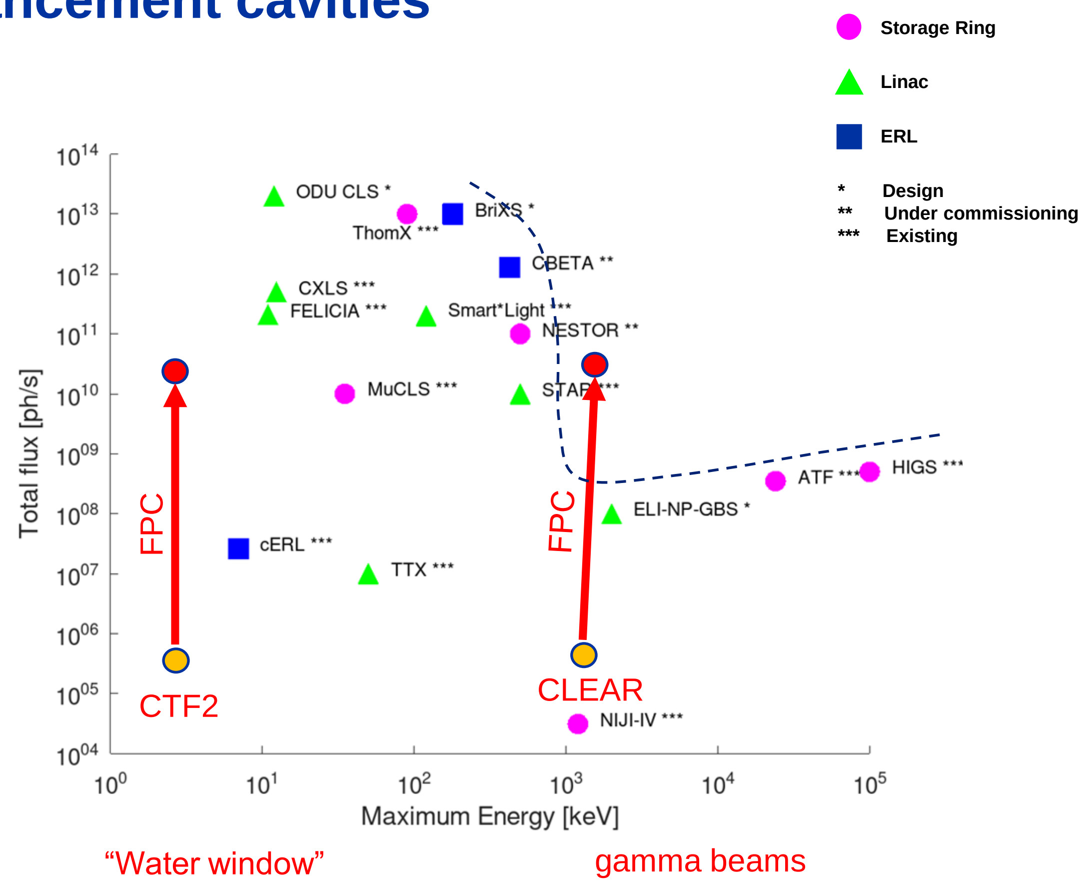
- **CTF2 could serve as a test bench for soft X-ray generation with CBS.**
- **Installing a CsTe cathode would allow for the generation of high intensity bunches and significant R&D in burst-mode operated Fabry-Perot cavities.**
- **The distance from cathode to IP of $\sim$ 1 m would make the CTF2 source the most compact known ICS source.**
- **A measurement of the beam size at the IP would be needed to determine the minimum spot size achievable from the gun.**

home.cern

Performance of CERN CBS sources by optical enhancement cavities

Parameter	Unit	CTF2 + PHAROS + Copper	CTF2 + Cs_2Te + One Five	CLEAR + CALIFES	CLEAR + PHAROS	CLEAR + One Five
		Single bunch	Multi-bunch	Multi-bunch	Single bunch	Multi-bunch
Compton edge	keV	0.89	0.88	740	750	740
Electron energy	MeV	7	7	200	200	200
X-ray pulse duration	ps	0.7	6	5	0.7	6
Ph/bunch		5×10^4	2×10^2	3×10^3	3×10^5	2×10^3
Bunches		1	80	30	1	150
Total flux	Ph/s	5×10^5	2×10^5	9×10^5	3×10^6	3×10^5

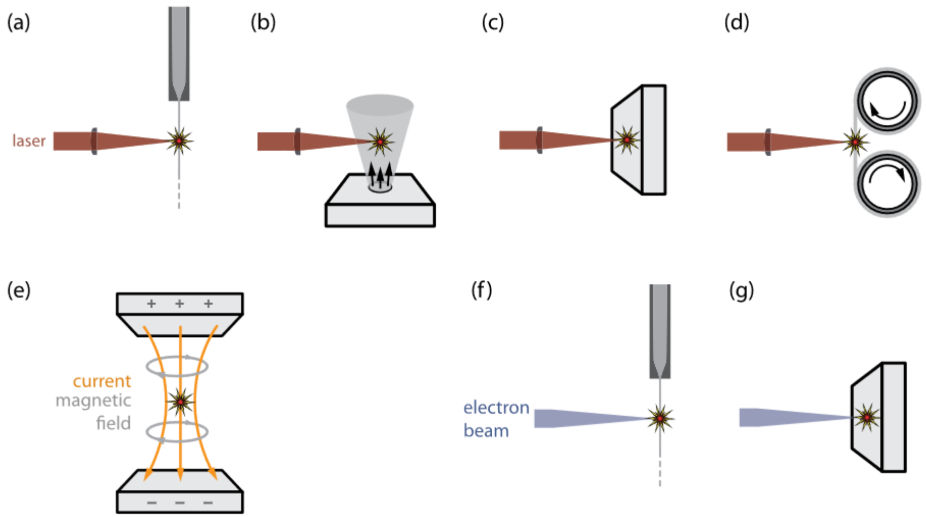
Parameter	Unit	CTF2 + OneFive + Cs_2Te + FPC	CLEAR + OneFive + FPC
Bunches/train		80	150
Max Effective gain		60	107
Max Effective energy	J	0.5	0.9
Total flux	ph/s	1×10^{10} @ 890 eV	3×10^{10} @ 740 keV



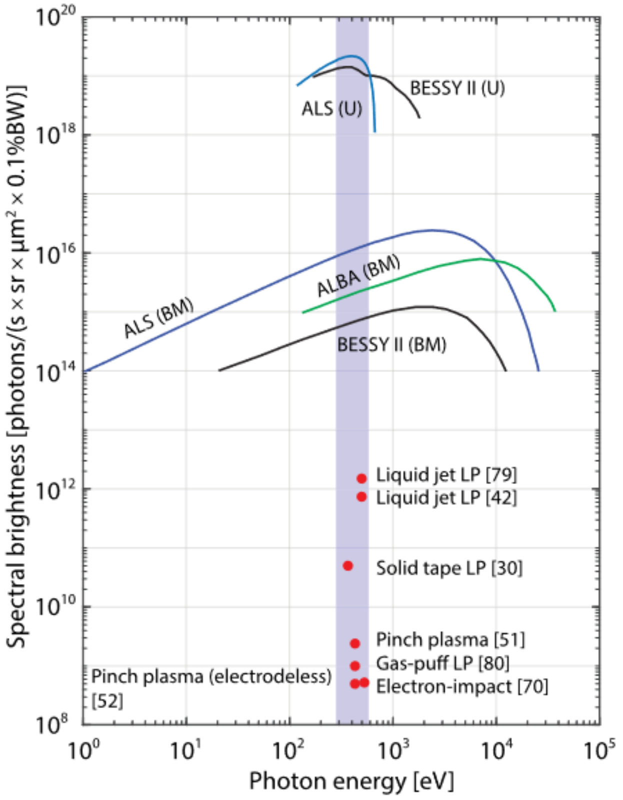
- **Without Fabry-Perot cavity (FPC), CBS experiment will have low flux.**
- **FPC requires EO comb as front-end of laser system to be effective.**

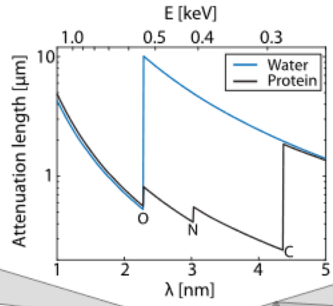
Water window experiments

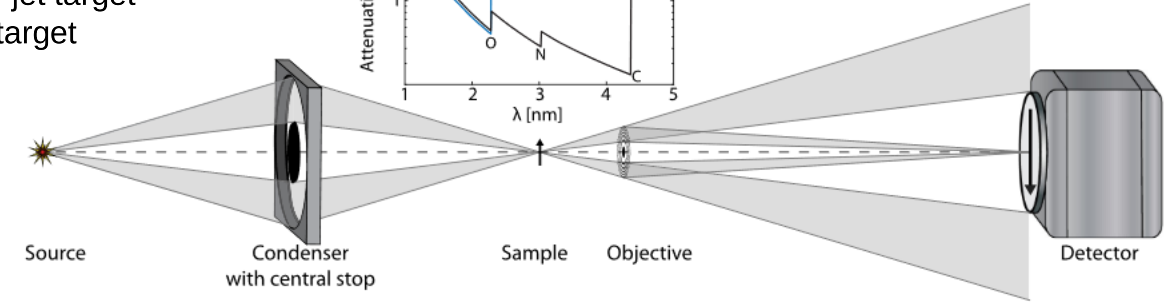
- **The 7 MeV electron beam provided by the injector can generate high intensity X-rays in the water window region.**
- **Compact set-up with up-to-date accelerator technology.**



Laser-plasm based
(a) liquid-jet target
(b) Gas-puff target
(c) Solid target
(d) Tape target
(e) Pinch-plasma discharge
Electron-impact
(f) Liquid-jet target
(g) Solid target







Measurables

Semiconductor based detectors are typically used for low energy X-rays.

Method	Detector	Requirements	Uses
Photon flux	Micro-channel plate, silicon drift detector	• High count rate (over 1e4 photons per bunch) • Fast response time	• Experimental check of simulated flux • Flux stability
Spectroscopy	HP Germanium detector, silicon drift detectors	• Good energy resolution (best from Germanium)	• Reproduction of spectrum • X-ray fluorescence (XRF)
Imaging	2D X-ray detectors	• High count rate • Small pixel size • Good spatial resolution	• Imaging of samples