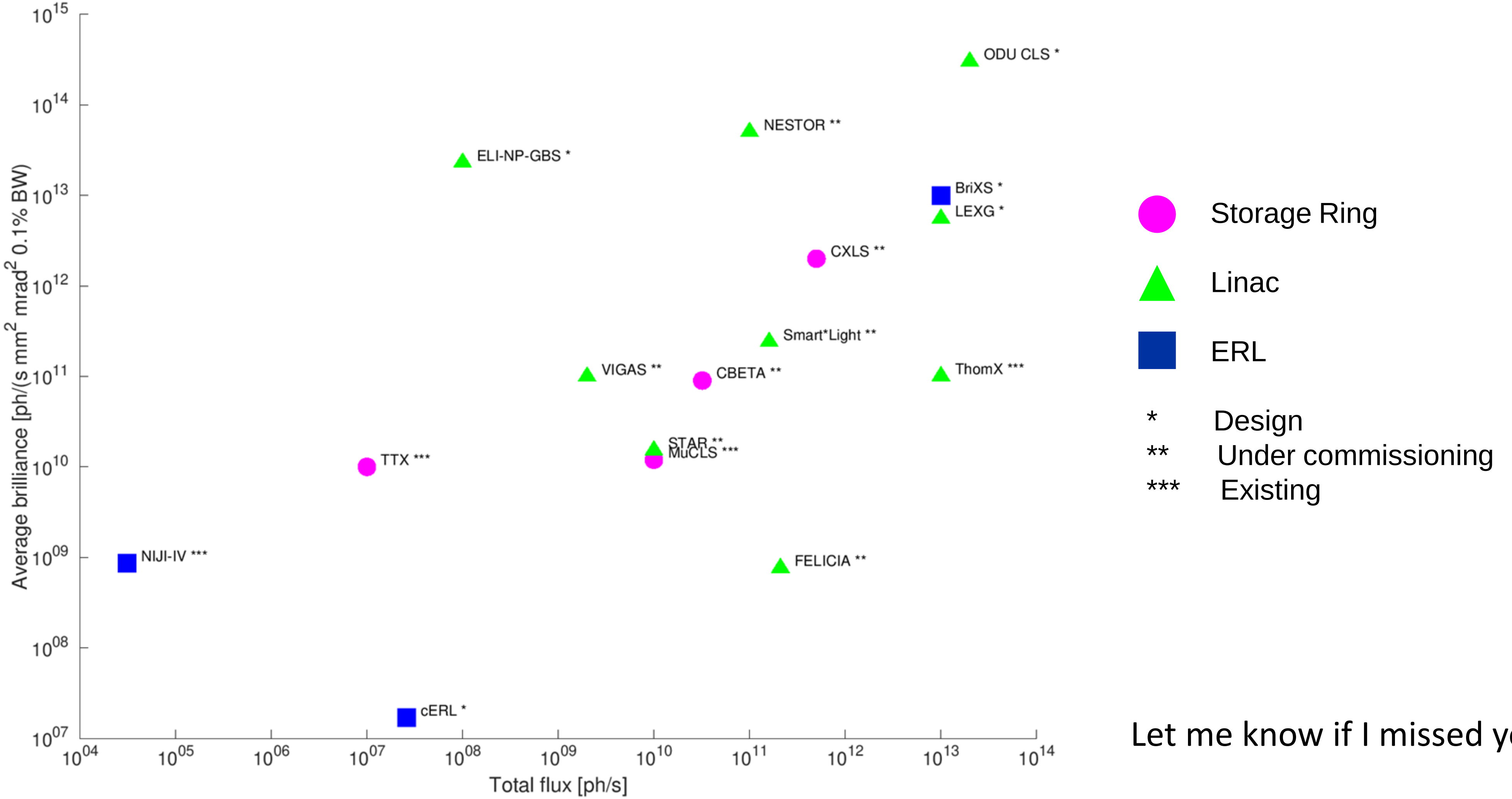
First ICS studies at CERN

Vlad Muşat

Supervisor: Andrea Latina

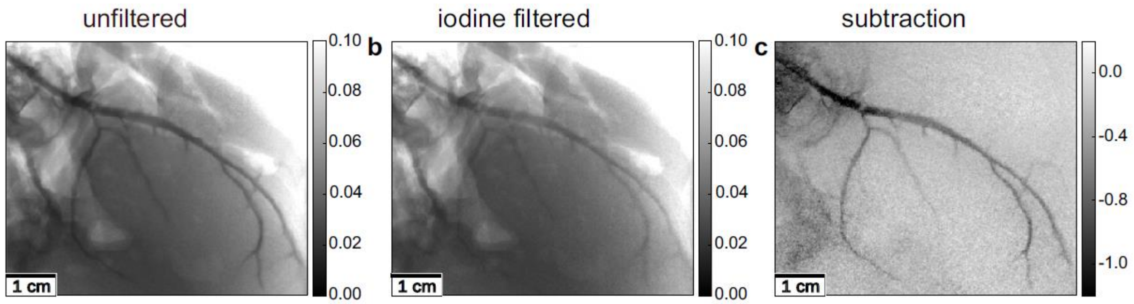
CompactLight Complementary Use and Opportunities – 8th, 9th November 2021

Landscape of ICS sources



Let me know if I missed your source!

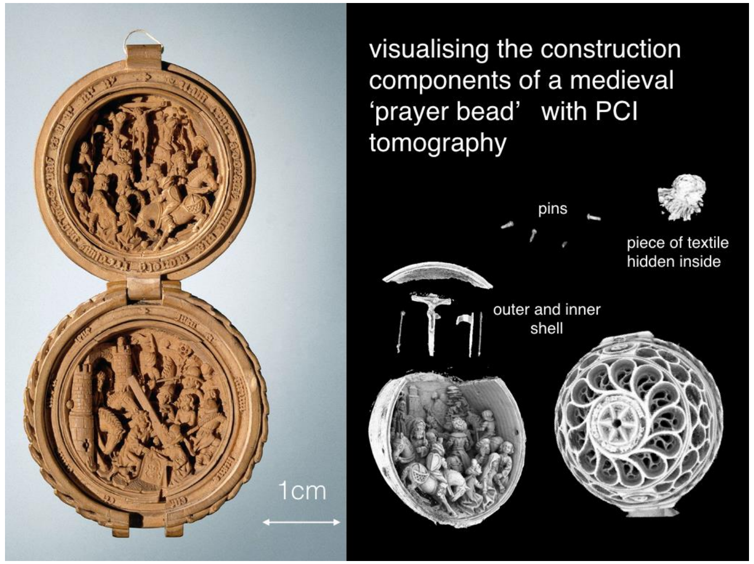
Potential applications



Ref: Kulpe, S., Dierolf, M., et al (December 10, 2018). K-edge subtraction imaging for coronary angiography with a compact synchrotron X-ray source. *Plos One, 13,* 12.)

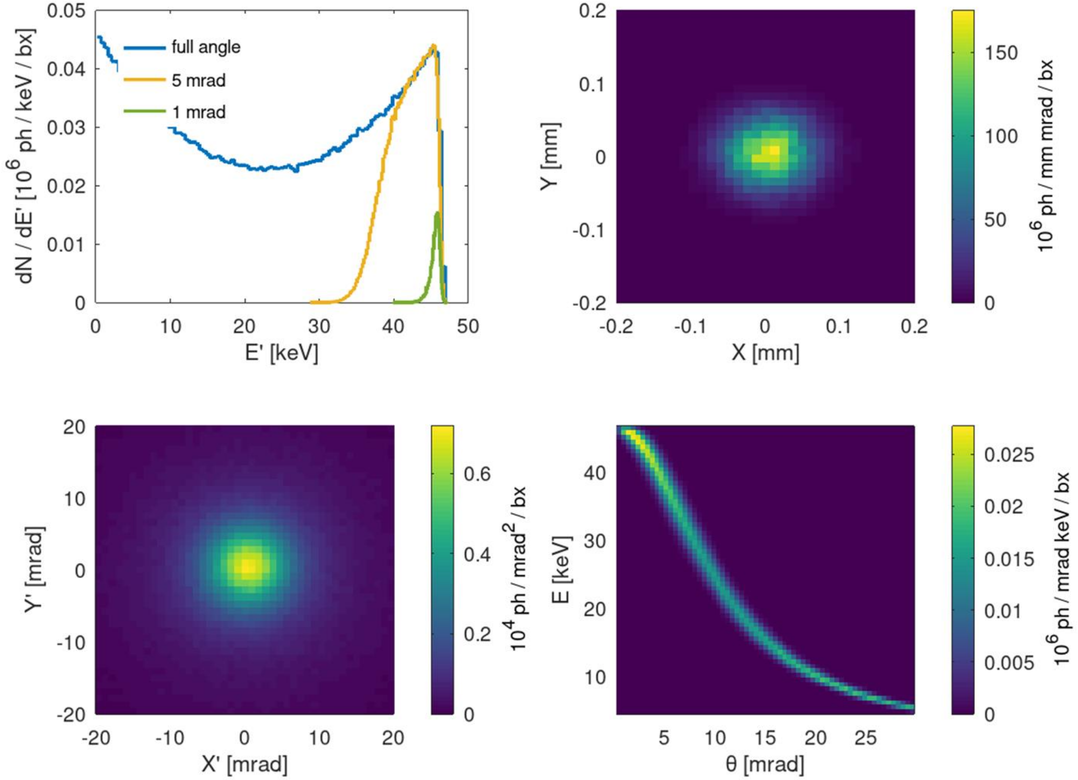
- Many applications were a result of previous studies at synchrotrons. ICS sources offer a more compact and accessible method to conduct such experiments, and there is hope that in the near future such devices will also be implemented in hospitals or laboratories.
- The main challenge currently is achieving high intensity and high energy x-rays, similar to the ones in synchrotron sources.
- Tomographies in particular have already been extensively studied.

Name	E_{Xray} [keV]	$\mathcal{F}$ [ph/s]	BW [%]	σ_{Xray} (at IP) [μm]	σ_{Xray} (at sample) [mm]	Θ [mrad]
K-edge subtraction	33.7	3×10^{10}	4.5	6	16	4
Phase contrast imaging	25	2.4×10^{9}	4	39×45	16	4
Microbeam radiation therapy	25	10^{13}	3.6	70	4	1.5
FLASH therapy	6.000–10.000	10^{14}	-	50	17	-
Protein crystallography	7–35	10^{13}	1.4	30	30	2
XRF	6.5-92	3×10^{10}	1-3	20	20×10^{-3}	-
Nuclear waste management	1.000–5.000	2.2×10^{13}	0.2	35	-	-



Ref: Reischig, P., et al (March 09, 2009). A note on medieval microfabrication: The visualization of a prayer nut by synchrotron-based computer X-ray tomography. *Journal of Synchrotron Radiation, 16,* 2, 310-313.

Code benchmark – RF-Track



ThomX: RF-Track

- RF-Track, developed by Andrea Latina [1], was used to simulate ICS sources at the laser and electron beam interaction point (IP).
- Pictured are RF-Track and CAIN simulation results for ThomX [2].
- The runtime for CAIN was **3276 seconds**, while for RF-Track, **0.67 seconds**.

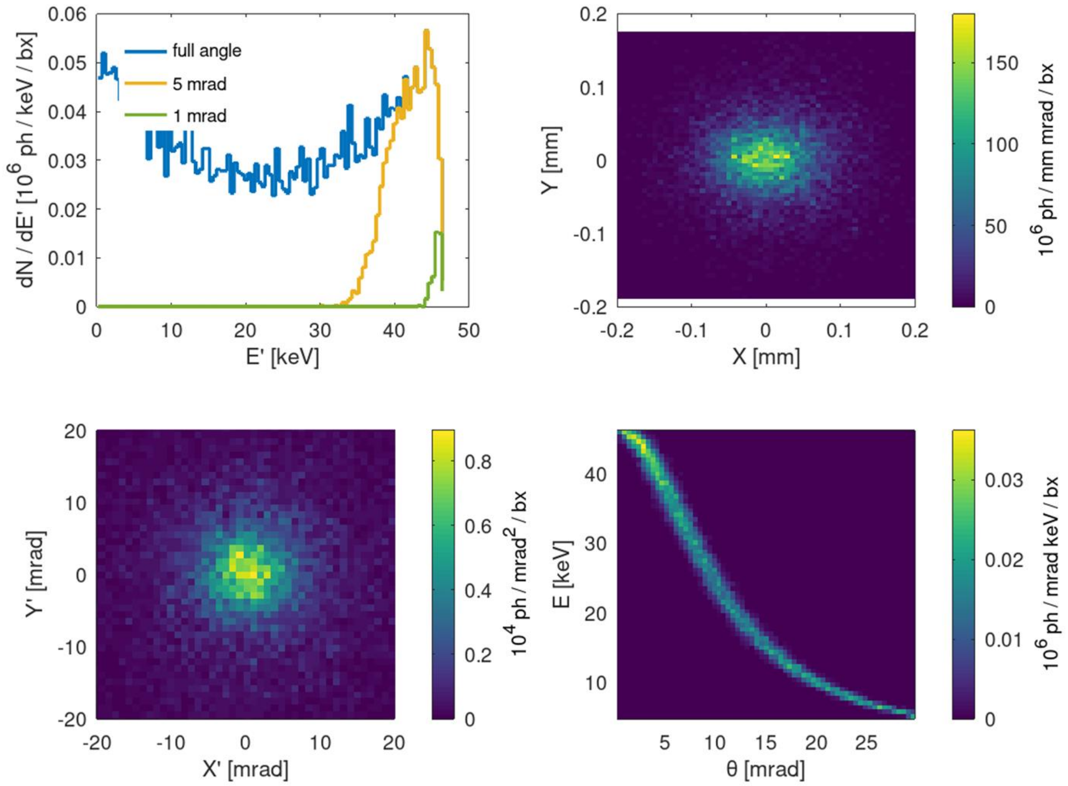
Parameter	Unit	CAIN	RF-Track	Analytic
Nb. of simulated electrons		10^7	10^4	-
Nb. of generated photons		2153	1.3×10^6	-
Runtime	s	3276	0.67	-
Total flux	10^{13} ph/s	2.83	2.52	2.54
Brilliance	(1)	3.83	3.73	3.77

$^{(1)}10^{11}$ph/(s mm^2 mrad^2 0.1%BW)

Acknowledgements
Alessandro Variola
Irina Chaikovska

[1] Andrea Latina, "RF-Track Reference Manual", CERN, Geneva, Switzerland, June 2020.
[2] A. Variola, J. Haissinski, A. Loulergue, F. Zomer, (eds). ThomX Technical Design Report. 2014, 164

Code benchmark - CAIN



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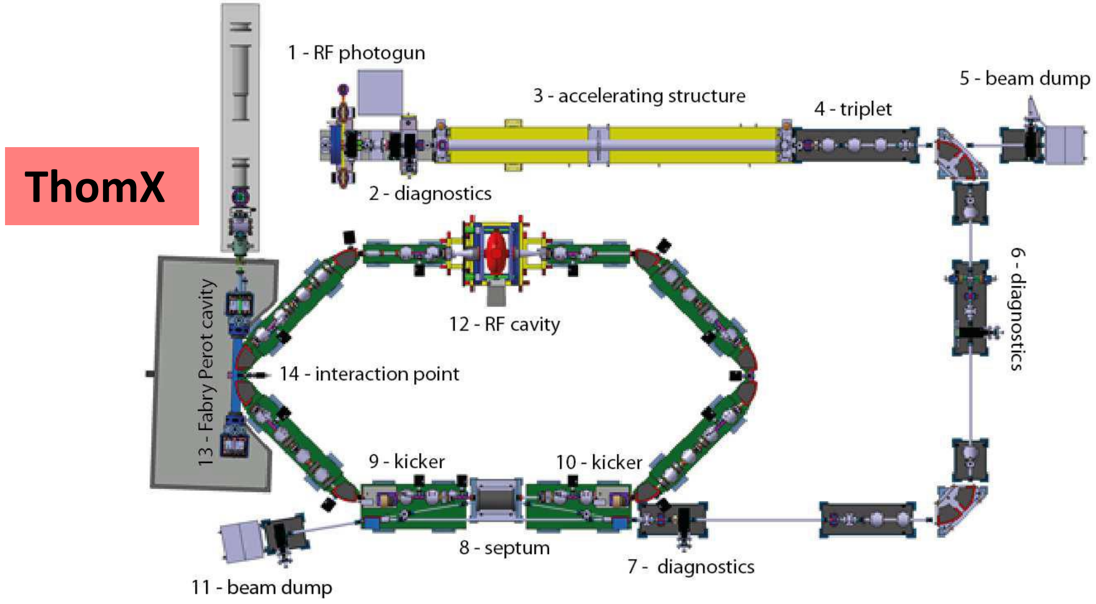
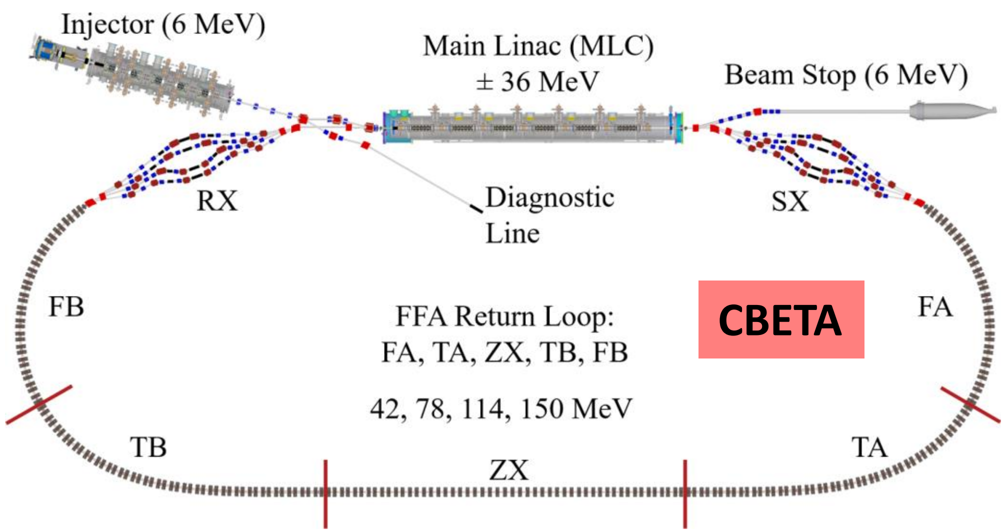
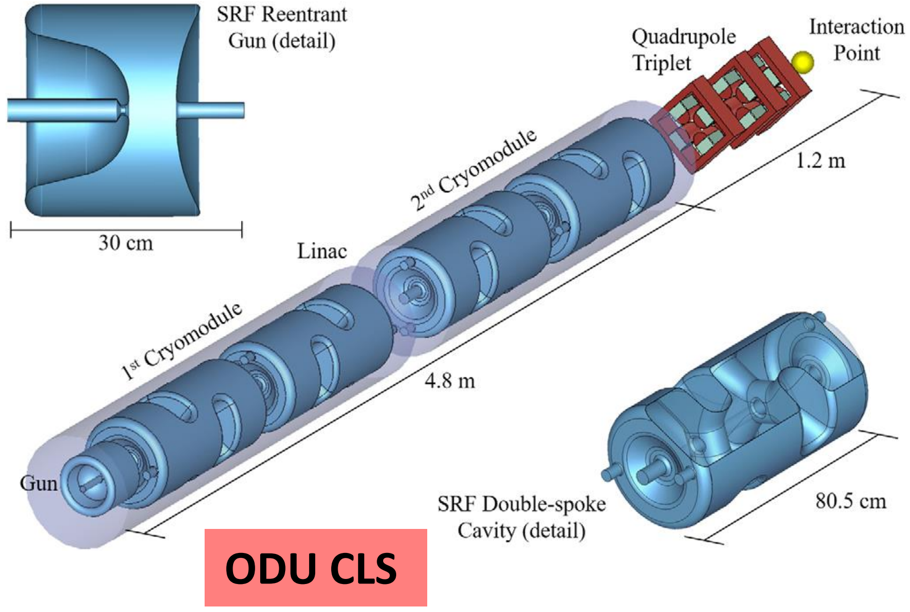
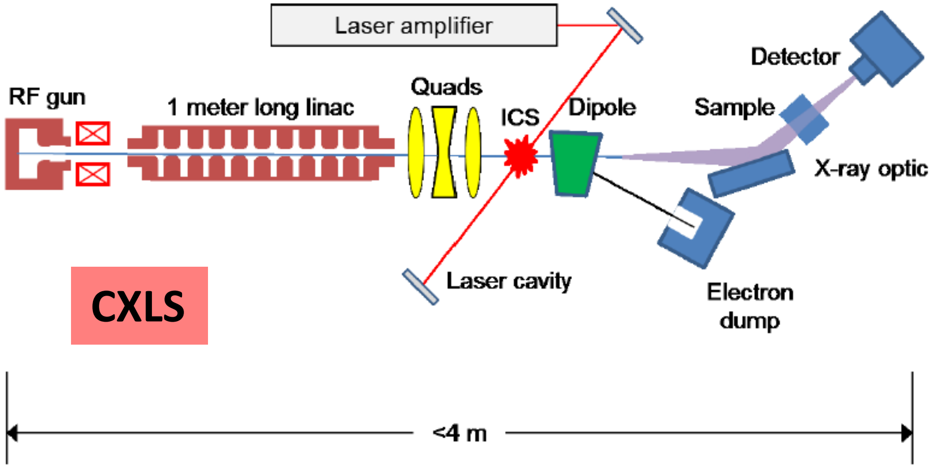
ICS sources used for RF-Track benchmark

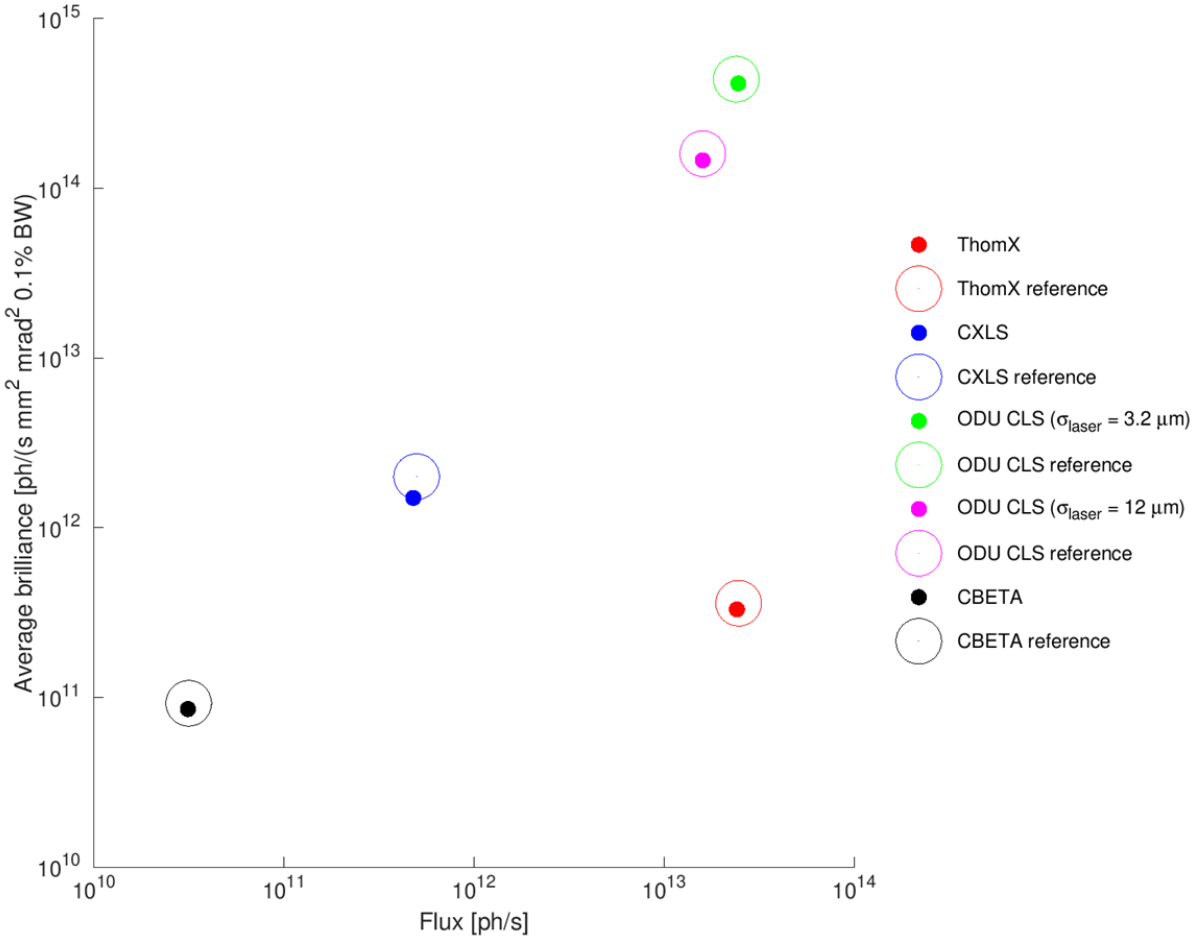








Benchmark of flux and brilliance calculations



- Sources were chosen based on their current status (existing, in development, or design-only) and performance: CXLS [1], CBETA [2], ThomX [3] and ODU CLS [4].
- Errors in simulation were determined from standard deviation of results from 10 runs per source. They were too small to be noticeable in the plot.

Differences between reference values could be attributed to:

1. Use of different simulation software. CAIN or COMPTON were typically used for ICS simulations at IP. [5]

[1] Emilio A. Nanni, William S. Graves, and David E. Moncton "From incoherent to coherent x-rays with ICS sources", Proc. SPIE 9590, *Advances in Laboratory-based X-Ray Sources, Optics, and Applications IV*, 959006 (26 August 2015)

[2] Deitrick, Kirsten, Georg H. Hoffstaetter, Carl Franck, Bruno D. Muratori, Peter H. Williams, Geoffrey A. Krafft, Balša Terzić, Joe Crone, and Hywel Owen. 2021. "Intense Monochromatic Photons Above 100 keV from an Inverse Compton Source". *Physical Review Accelerators and Beams.* 24, no. 5.

[3] Kevin Dupraz, et al. 2020. "The ThomX ICS Source". *Physics Open.* 5: 100051.

[4] Deitrick, K. E., Krafft, G. A., Terzic, B., Delayen, J. R., Krafft, G. A., Delayen, J. R., & Deitrick, K. E. (August 24, 2018). High-brilliance, high-flux compact inverse Compton light source. *Physical Review Accelerators and Beams*, 21, 8.)

[5] Brown, W. J., et al. (June 01, 2004). Experimental characterization of an ultrafast Thomson scattering x-ray source with three-dimensional time and frequency-domain analysis. *Physical Review Special Topics - Accelerators and Beams, 7*, 6.)

XLS and HPCI electron beam parameters

Acknowledgements
Roberto Corsini
Steffen Doebert
David Alesini

Parameter	Symbol	CompactLight	HPCI	Unit
Electron beam energy	E_e	100–300	100–300	MeV
Repetition rate	f	1000	10	Hz
Bunches per train		50 (2)	1000	
Collision rate	f_{eff}	50	10	10^3 s^{-1}
Bunch length	σ_z	1	1	ps
Bunch charge	Q	200 (75)	300	pC
Bunch spacing		5	1/3	ns
Normalised emittance	$\epsilon_{x,y}^N$	0.3 (0.15)	5	mm mrad

- CompactLight (XLS) and high pulse current injector (HPCI) can provide high electron beam energies with X-band linacs.
- To maximise flux
  - increase *Q*, number of bunches per train, and laser pulse energy

$$N_\gamma = \sigma_c \frac{N_e N_{\mathrm{laser}} \cos(\phi/2)}{2\pi\sigma_y\sqrt{\sigma_x^2\cos^2(\phi/2)+\sigma_z^2\sin^2(\phi/2)}}$$

$$\mathcal{B} \approx \frac{\gamma^2 \mathcal{F}_{0.1\%}}{4\pi^2\epsilon_x^N\epsilon_y^N}$$

Note: modified value (baseline value)

Laser: Preliminary considerations

- A laser similar to TRUMPF's 1 kW Dira 1000 [1] was considered.

XLS

- 1 kW and f = 1 kHz -> 1 J/pulse, 50 bunches/pulse -> E_p = 20 mJ
- Bunch spacing = 5 ns -> 200 MHz enhancement cavity

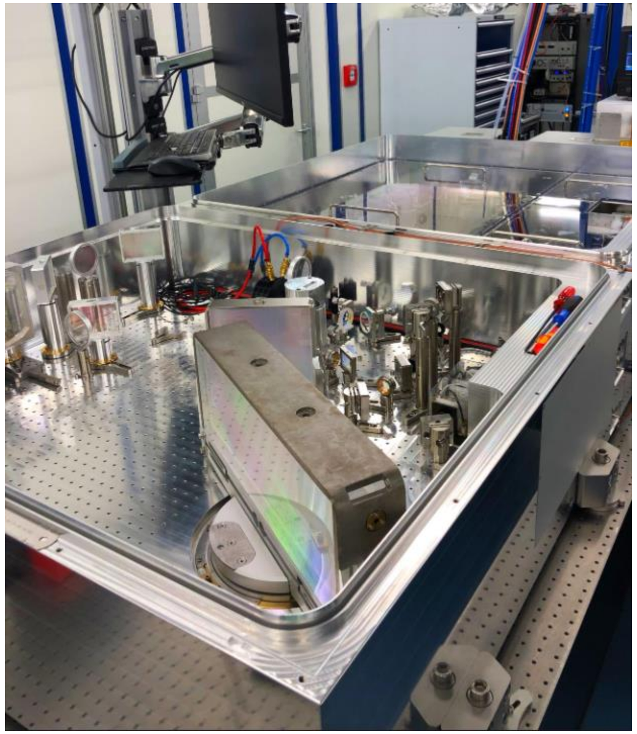
HPCI

- 1 kW and f = 10 Hz -> 100 J/pulse, 1,000 bunches/pulse -> E_p = 100 mJ
- Bunch spacing = 1/3 ns -> 3 GHz enhancement cavity

Enhancement cavities could be used

- In CW for XLS, given a bunch spacing of 5 ns -> **E_p = 50 mJ**
- In burst mode for HPCI, given a bunch spacing of 1/3 ns -> **E_p = 6.6 J**

Parameter	Quantity	Units
Laser power	1000	W
Pulse length, τ	0.6	ps
Wavelength, λ	1000	nm



Acknowledgements
Eduardo Granados

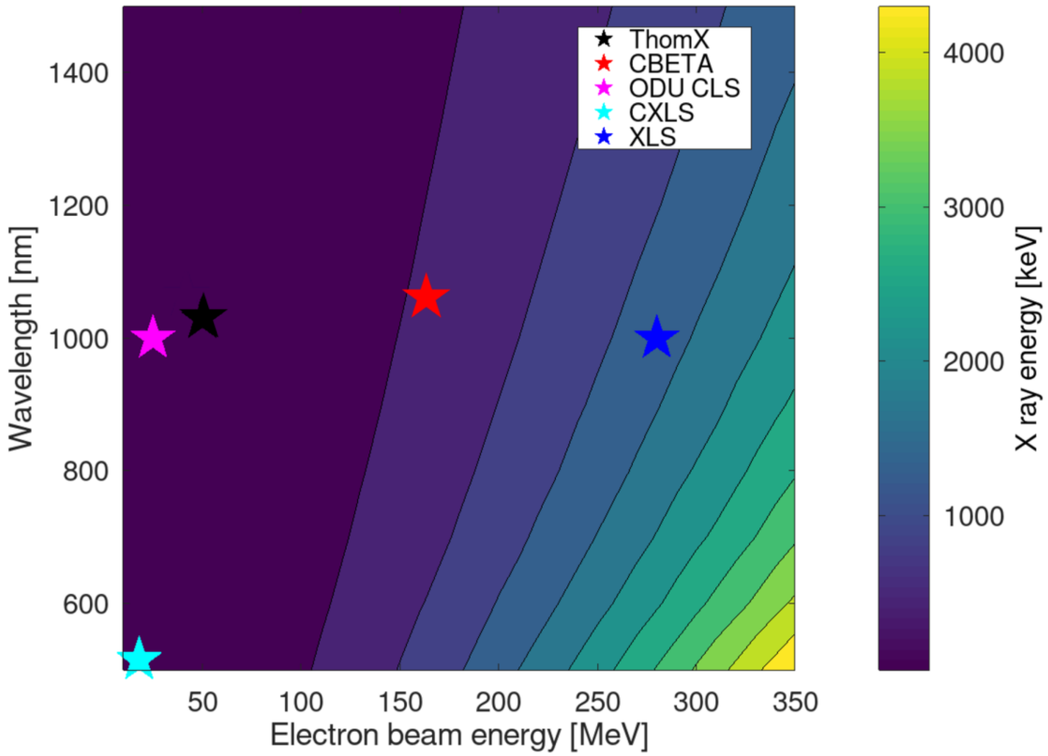
[1] T. Metzger (November 6 2019), Ultrafast Thin-Disk Amplifiers, Talk S55.

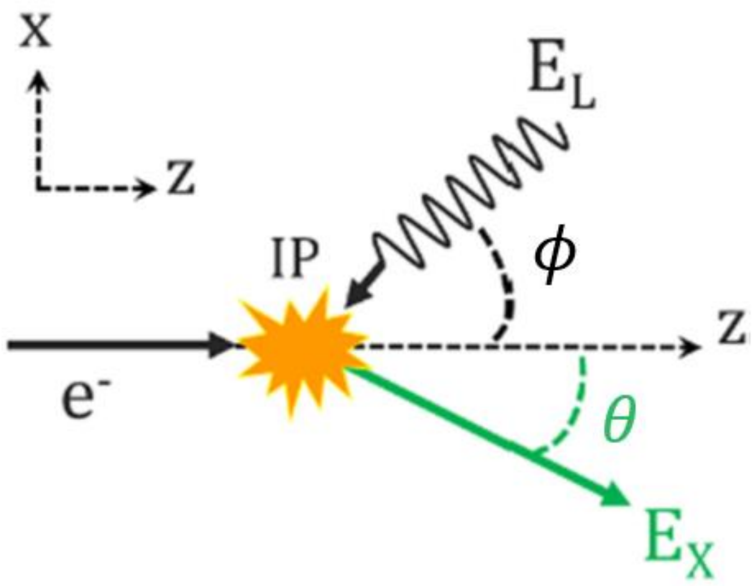
Parametric scans of X-ray energy

- Expect a dependence of the x-ray energy on laser wavelength and electron beam energy from [1]

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

where E_{X} is the x-ray energy, E_{laser} the laser photon energy, θ the scattering angle, ϕ the crossing angle.

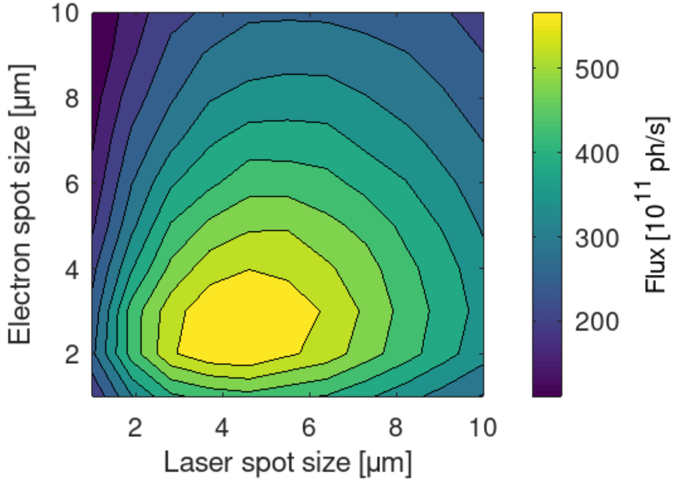




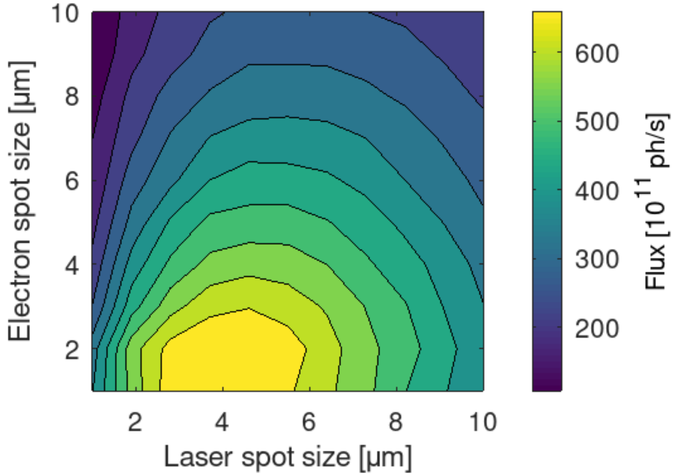
[1] Jacquet, M. (January 01, 2016). Potential of compact Compton sources in the medical field. *Physica Medica, 32,* 12, 1790-1794.

HPCI & XLS: Spot size scans (full angle)

HPCI

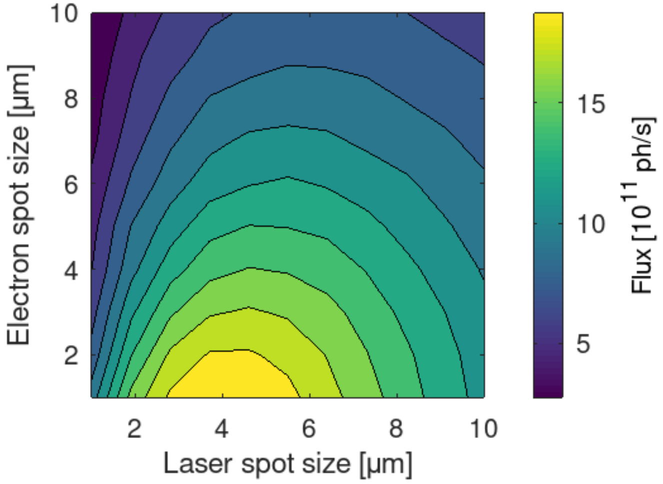


100 MeV

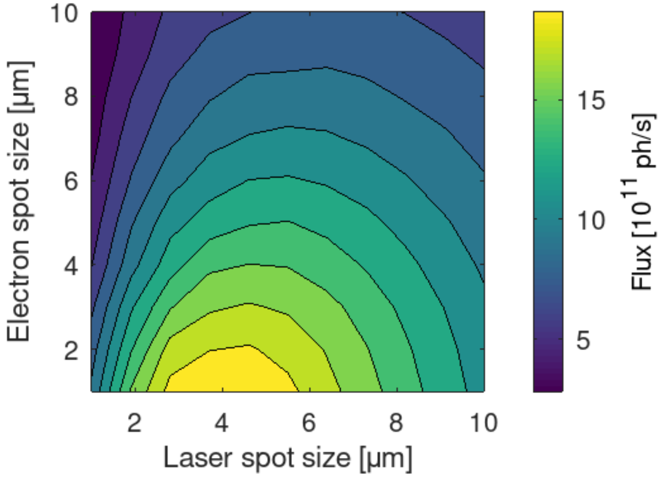


300 MeV

XLS



100 MeV



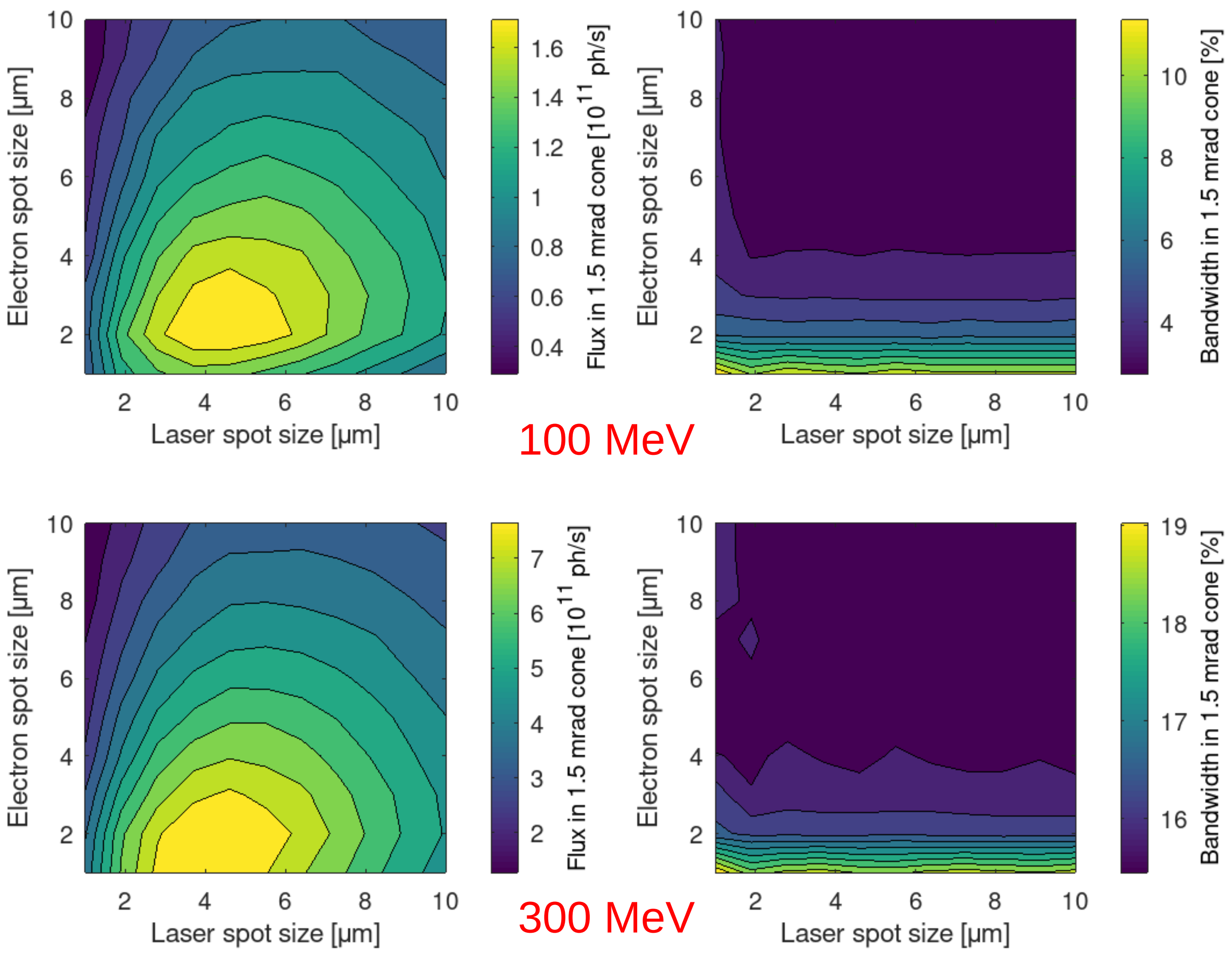
300 MeV

- Dira 1000 laser was used, along with HPCI and XLS electron gun
- Applications typically use flux in a 1-2 mrad cone
- Can reduce bandwidth using X-ray monochromators at the expense of flux
- Values for table given for maximum flux

Parameter	Unit	HPCI		XLS	
Electron beam energy	MeV	100	300	100	300
Electron spot size	µm	2–4	0.5–2.5	0.5–2.0	0.5–2.0
Laser spot size	µm	3–6	3–6	3–6	3–6
Total flux	ph/s	5.0×10^{13}	6.0×10^{13}	1.5×10^{12}	1.5×10^{12}
Average brilliance	(1)	3.0×10^{12}	3.0×10^{13}	3.0×10^{13}	2.5×10^{14}

(1) ph/(s mm^2 mrad^2 0.1%BW)

XLS: Spot size scans (1.5 mrad cone)



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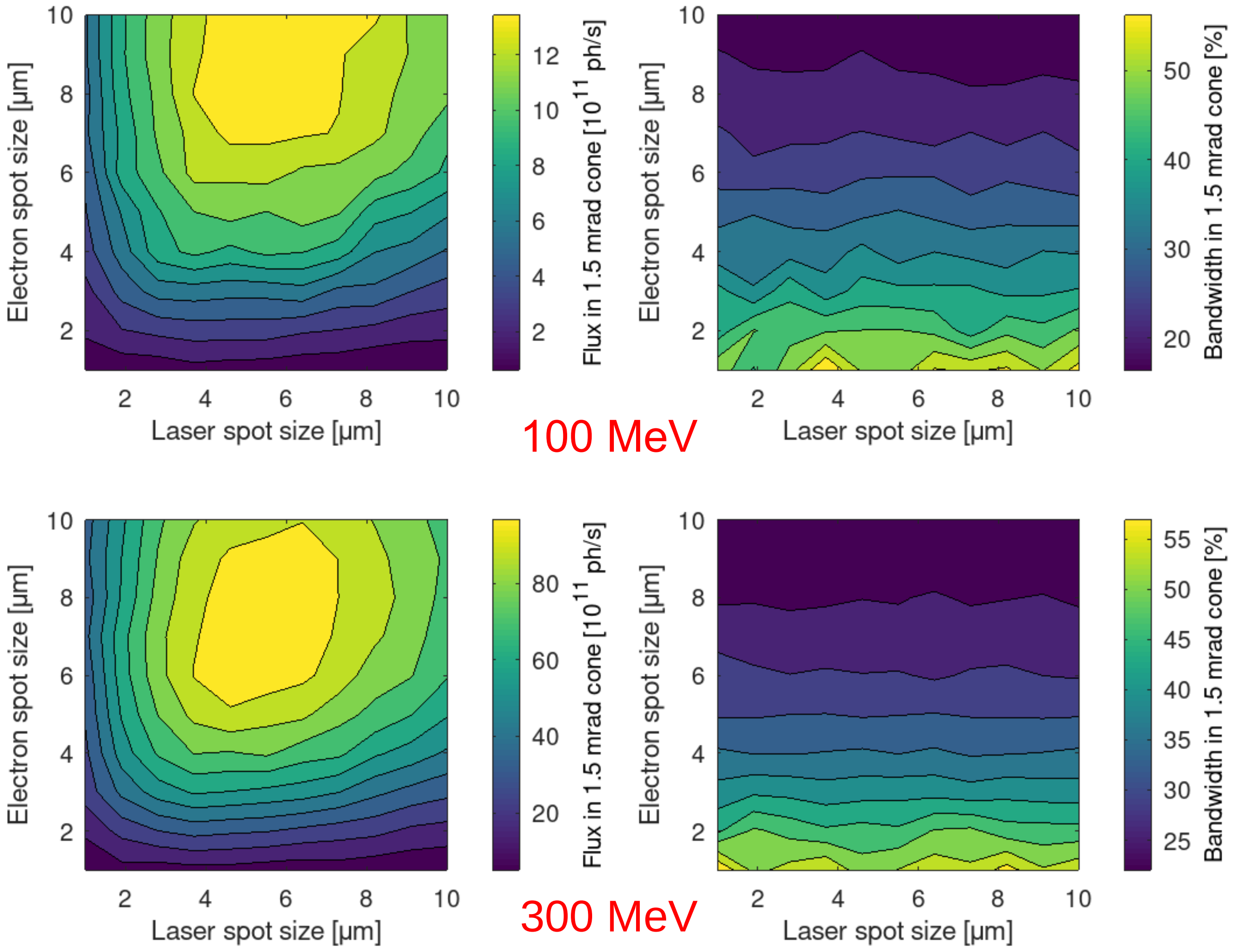
XLS parameter	Unit	100 MeV	300 MeV
Electron spot size	µm	1–4	0.5–3
Laser spot size	µm	3–6	3–6
Flux in 1.5 mrad cone	10^{11}ph/s	1.6	7.0
BW in 1.5 mrad cone	%	4–8	16–19

HPCI: Spot size scans (1.5 mrad cone)



- Dira 1000 laser was used, along with HPCI electron gun
- Applications typically use flux in a 1-2 mrad cone
- Can reduce bandwidth using X-ray monochromators at the expense of flux
- Values for table given for maximum flux

HPCI parameter	Unit	100 MeV	300 MeV
Electron spot size	µm	7–11	5–10
Laser spot size	µm	4–8	3–7
Flux in 1.5 mrad cone	10^{11}ph/s	12	80
BW in 1.5 mrad cone	%	10–20	25–35

Preliminary parameters

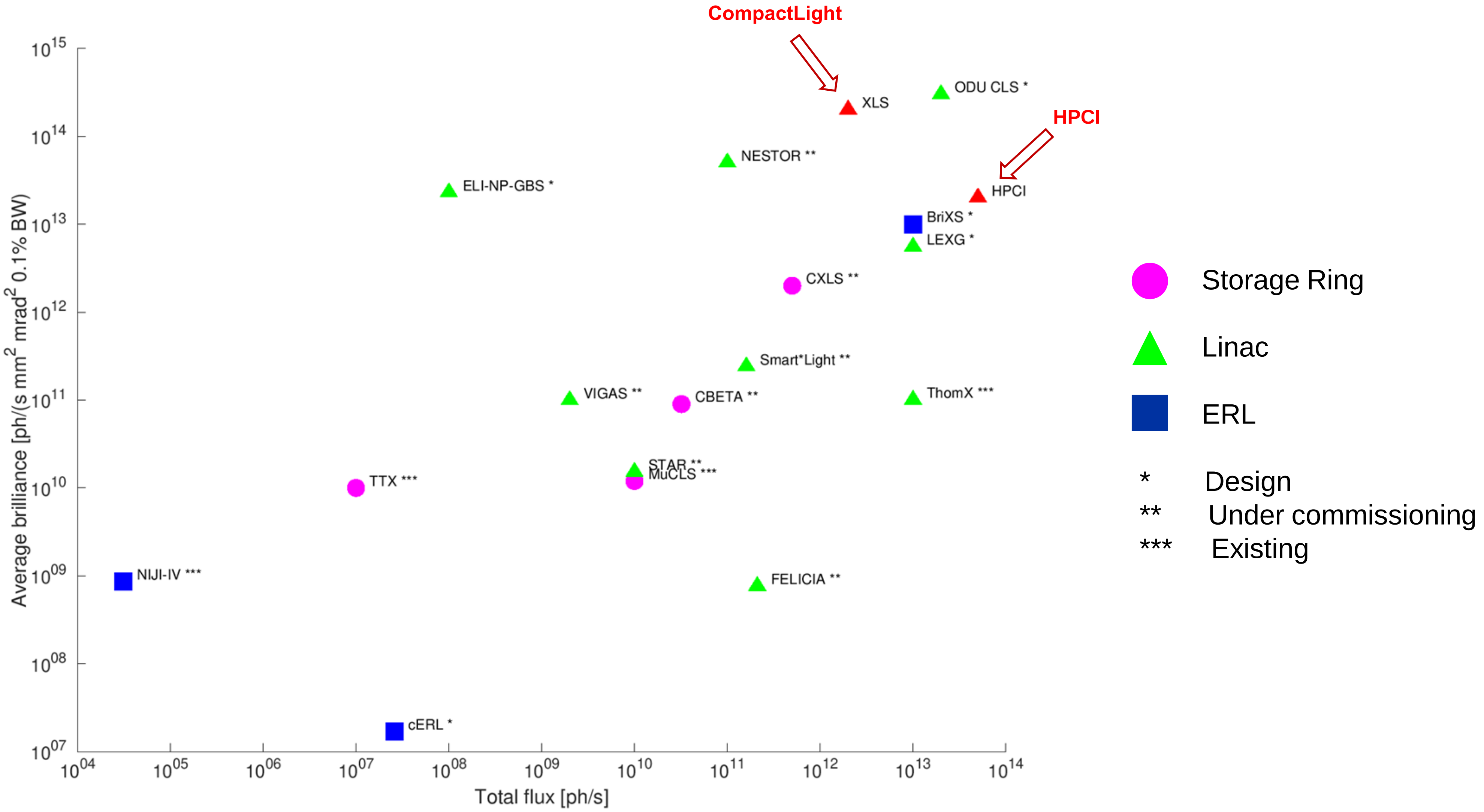
Parameter	Symbol	CompactLight		HPCI		Unit
Electron beam energy	E_e	100	300	100	300	MeV
Repetition rate	f	1000		10		Hz
Bunches per train		50		1000		
Collision rate	f_{eff}	50		10		10^3 s^{-1}
Bunch length	σ_z	1		1		ps
Bunch charge	Q	200		300		pC
Bunch spacing		5		1/3		ns
Normalised emittance	$\epsilon^N_{x,y}$	0.3		5		mm mrad
Electron spot size	σ_e	1–4	0.5–3.0	7–11	5–10	µm
Laser pulse energy	E_p	50		6.6×10^3		mJ
Pulse length	τ	0.6		0.6		ps
Wavelength	λ	1000		1000		nm
Laser spot size	σ_{laser}	3–6	3–6	4–8	3–7	µm
Total flux	$\mathcal{F}$	1.8×10^{12}	1.8×10^{12}	5.0×10^{13}	6.0×10^{13}	ph/s
Flux in 1.5 mrad	$\mathcal{F}_{1.5\text{ mrad}}$	1.6×10^{11}	7.0×10^{11}	8.0×10^{12}	8.0×10^{12}	ph/s
Average brilliance	$\mathcal{B}$	3.0×10^{13}	2.5×10^{14}	0.3×10^{13}	3.0×10^{13}	(1)
Bandwidth in 1.5 mrad	BW$_{1.5\text{ mrad}}$	4–8	16–19	10–20	25–35	%

(1) ph/(s mm^2 mrad^2 0.1%BW)

- Results for flux and brilliance given by electron and laser spot sizes required for maximum values

$$\mathcal{B} \approx \frac{\gamma^2 \mathcal{F}_{0.1\%}}{4\pi^2 \epsilon^N_x \epsilon^N_y}$$

Landscape of ICS sources



Conclusions

- Electron beam parameter ranges were determined, based on CompactLight and HPCI injectors
- Laser parameters based on TRUMPF's 1 kW Dira 1000 laser were used
- Can achieve flux of $10^{11\text{-}13}$ ph/s, among the largest for ICS sources, along with X-ray energies of 1-5 MeV
- Potential applications for high energy X rays include FLASH therapy and nuclear waste management
- Next steps: imperfection and tolerance studies.

	Symbol	CompactLight		HPCI		Unit
Electron beam energy	E_e	100	300	100	300	MeV
Total flux	$\mathcal{F}$	4–18	4–18	200–500	200–600	10^{11}ph/s
Average brilliance	$\mathcal{B}$	50–300	500–2500	10–30	100–300	(1)
Flux in 1.5 mrad	$\mathcal{F}_{1.5\ \mathrm{mrad}}$	0.4–1.6	2–7	2–12	20–80	10^{11}ph/s
Bandwidth in 1.5 mrad	$\mathrm{BW}_{1.5\ \mathrm{mrad}}$	4–10	16–19	20–50	25–55	%

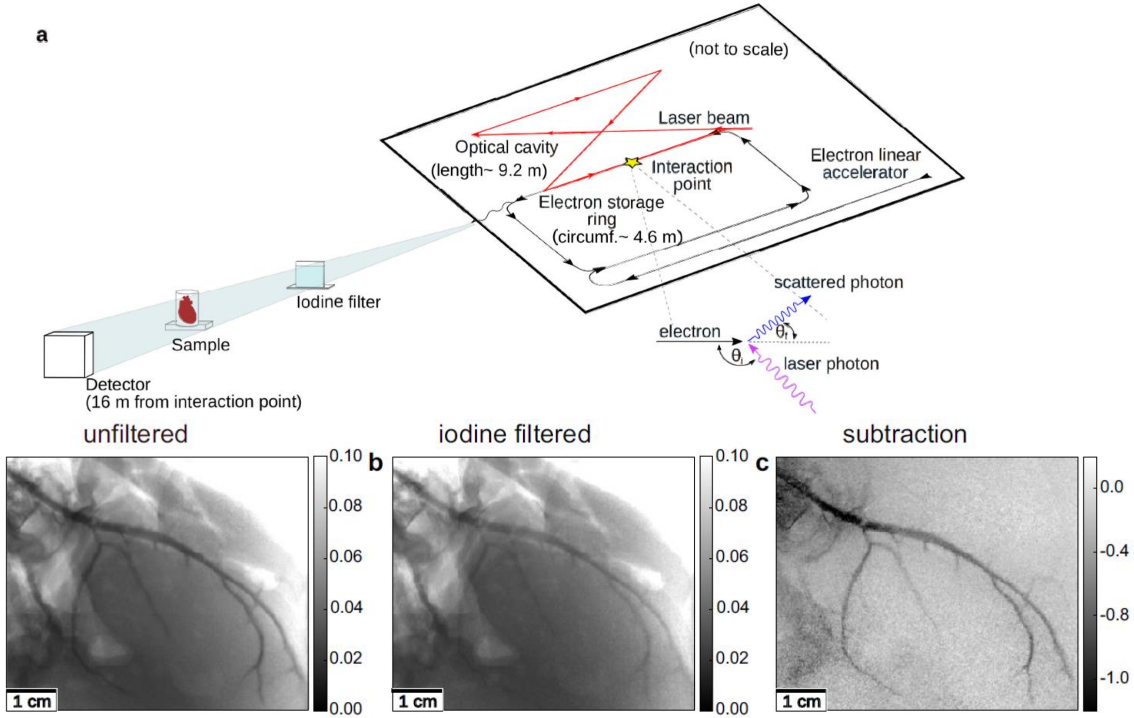
(1) 10^{11}ph/(s mm^2 mrad^2 0.1%BW)

Extra slides

	Electron beam parameters							Laser beam parameters						X-ray parameterss			
Name	Kinetic energy/MeV at IP	Bunch charge/pC	Emittance in x/ um rad	Emittance in y/ um rad	Rms transverse radius x/um	Rms transverse radius y/um	Bunch length (pulse length)/ps	Laser wavelength/ nm	Pulse length/ps	Pulse energy/mJ	Spot size x/um at IP	Spot size y/um at IP	Repetition rate/MHz	Minimum X-ray energy/keV	Maximum X-ray energy/keV	Total flux/ ph/s	Rms transverse source size/um
ELSA	17.7	4.00E+02	7.8	18.9	105	73	34	532	34	65	84	64	72.2	11	11	29000	44
ThomX	70	1000	2	9	45	100	5.00	1030	5	28	40	40	16.7	45	90	1E+13	40
MuCLS	45	250					50	1064	26	5.00E-04	42		64.91	15	35	1E+10	50
TTX	46.7	200	2.70E+00	3.50E+00	32	32	10	800	0.1	300	20	20	75	30	50	1.70E+12	50
ELI-NP-GBS	750	250	0.4	0.4	15.9	15.9	0.926667	515	1.5	400	15.5	10.5	3.20E-03	200	20000	1E+08	15.5
STAR	155	1100	2.1	1.1	18.8	18.8	5	1064	5	500			1.00E-04	20	500	1E+10	
NESTOR	25	500	1.47E-02	1.47E-02	120	120	0.5 cm	1064	10	1	1.00E+02	1.00E+02	58	30	500	1.00E+13	70
Smart*Light	5	10	1.395	1.6	5	9.1	0.478	400	0.03	10			0.001	60	120		
CBETA	150	32	0.3	0.3			4.3	1000	9	0.062	25	25	162.5	33.5	427	1.3E+12	6
ALICE	35	80	10	10			0.6	100		700			81.25	21.5	21.5		
cERL	20	0.355	0.32	0.28	78	16	2	1064	10	0.0615	24	32	162.5	6.95	6.95	26000000	
BriXSino	100	200	0.6	1.5	19.4	23.4	0.3	1030 and 257.5	2	7.5	40	80	100	20	180	1.00E+13	14
NIJI-IV	310		0.06	0.0084			0.58	355		300			0.00001	1200	1200	31000	
HIγS		40	0.35	0.015	140	20		1064	500	0.4			0.000025	1000	3000	5e7 - 5e8	
CXLS	22.5	100	0.01	0.01	3	3	0.1	515		200			0.001	12.4	12.4	5.00E+11	2.4
FELICIA	40	50	8	8	42	64	2	3000	2		30	30	1.43	10.9	10.9	2.10E+11	
ODU CLS	25	10	0.1	0.13	3.4	3.8	4.5	1240	2		3.2	3.2	100	1.2	12	2E+13	3
LEXG	1.75E+04	1.00E+03	1.1	0.6	15	8	10.00			10			1.00E-05			5.00E+10	

K-edge subtraction

- K-edge imaging works by subtracting two images acquired before and after the K-edge absorption threshold of a contrast agent [1].
- Exploits the tunability and high energy properties of ICS sources.
- This technique is used in coronary angiography [2], and to test high-Z element drugs given x ray energies of ~ 80 keV [1].
- Depends on a precise X-ray mean energy of 33.18 keV, just above K-edge of iodine [1].
- The 10 min scan time achieved at the MuCLS is impractical for clinical settings, but improvements can be made to increase the x ray flux, which will decrease the acquisition time.

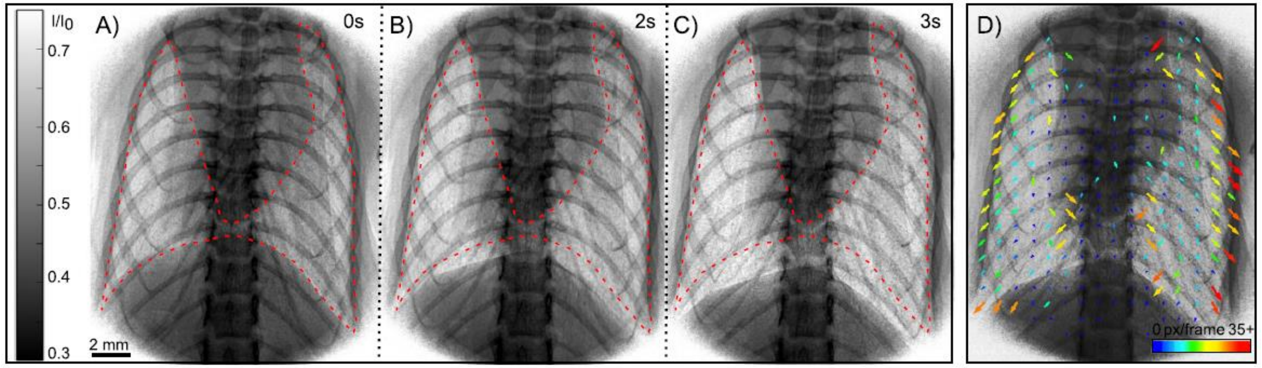


Ref: Kulpe, S., et al. (December 10, 2018). K-edge subtraction imaging for coronary angiography with a compact synchrotron X-ray source. *Plos One, 13,* 12.)

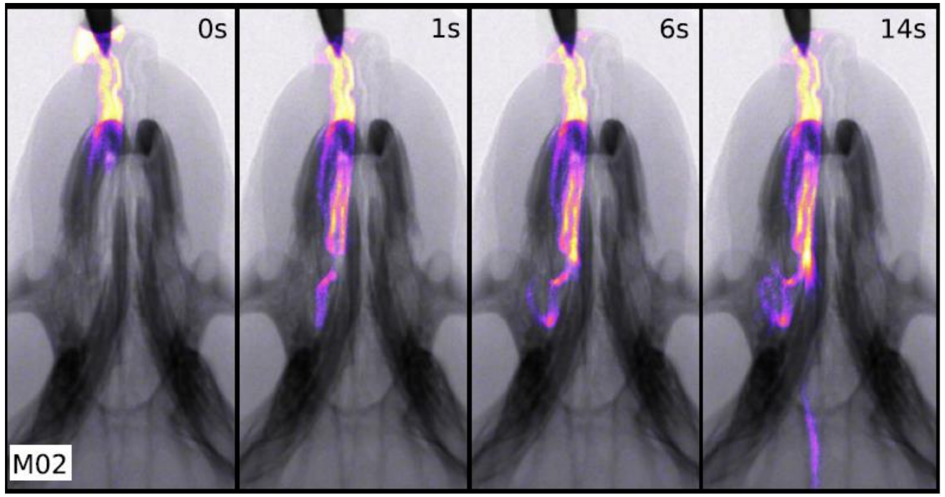
Name	Value	Units
Energy	33.7	keV
Total flux	3×10^{10}	ph/s
Bandwidth	4.5	%
Source size (at IP)	45	µm
Source size (at sample)	16	mm
Divergence	4	mrad

[1] Jacquet, M. (July 15, 2014). High intensity compact Compton X-ray sources: Challenges and potential of applications. *Nuclear Inst. and Methods in Physics Research, B, 331,* 1-5.
[2] Kulpe, S., et al. (December 10, 2018). K-edge subtraction imaging for coronary angiography with a compact synchrotron X-ray source. *Plos One, 13,* 12.)
[3] Kulpe, S., et al. (December 01, 2019). K-edge Subtraction Computed Tomography with a Compact Synchrotron X-ray Source. *Scientific Reports, 9,* 1.)

Phase contrast imaging



- In PCI, a quasi-spatial coherent radiation illuminates an object, which gives rise to a spatially varying phase shift. As the radiation propagates after the sample, parts of the wavefront interfere, resulting in a characteristic phase contrast pattern [1].
- The phase contrast signal can be visualised if the transverse coherence of the source is sufficiently large and the point source size sufficiently small [1].
- Studies in dynamic respiratory imaging were done at the MuCLS [2].
- Also benefits from small source size, and high flux.



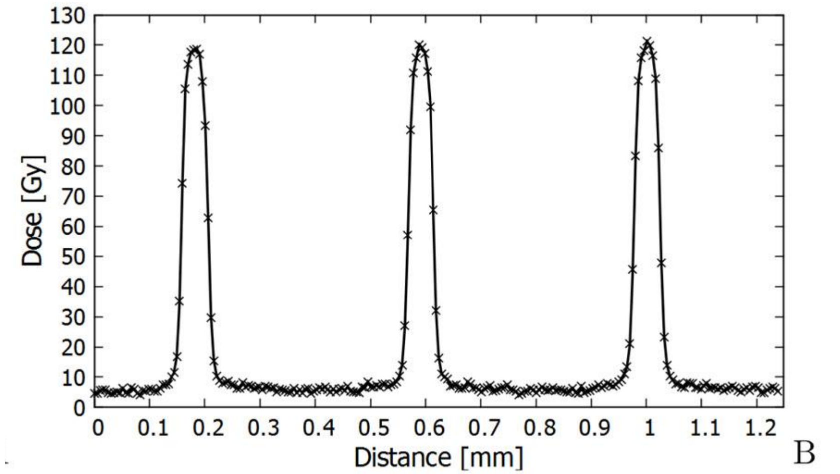
Ref: Gradl, R., et al., SpringerLink (Online service). (2018). In vivo Dynamic Phase-Contrast X-ray Imaging using a Compact Light Source. (Scientific reports.)

Name	Value	Units
Energy	25	keV
Total flux	2.4×10^9	ph/s
Bandwidth	4	%
Source size (at IP)	39×45	µm
Source size (at sample)	16	mm
Divergence	4	mrad

[1] Gradl, R., et al., SpringerLink (Online service). (2017). Propagation-based Phase-Contrast X-ray Imaging at a Compact Light Source. (Scientific reports.)
[2] Gradl, R., et al. SpringerLink (Online service). (2018). *In vivo Dynamic Phase-Contrast X-ray Imaging using a Compact Light Source*. (Scientific reports.)

Cancer Therapy

- It has been shown that ICS sources such as ThomX can reproduce beam parameters from Stereotactic Synchrotron Radiation therapy (SSRT) clinical trials. For 80 keV x ray energy, same flux as in SSRT studies was achieved (needed flux of 2×10^{12} ph/s). [1]
- Proof of principle microbeam radiation therapy (MRT) experiments have been done at the MuCLS, confirming their ability to slow tumour growth rate, despite the much lower dose rate with respect to SSRT [2].
- Requires x ray energies of 100-300 keV[3].
- The main considerations for the optimization of the MRT photon spectrum relate to
    i. Maximising the photon flux to allow for the required dose rate delivery.
    ii. Providing the necessary x-ray energy to reach deep-lying targets.
    iii. Maximising the peak-to-valley-dose ratio (PVDR). In this context, photon energies below 50 keV are considered not useful.
- “Abundant preclinical evidence demonstrates that MRT spares normal tissue more effectively than conventional radiation therapy, at equivalent tumour control.” [3]



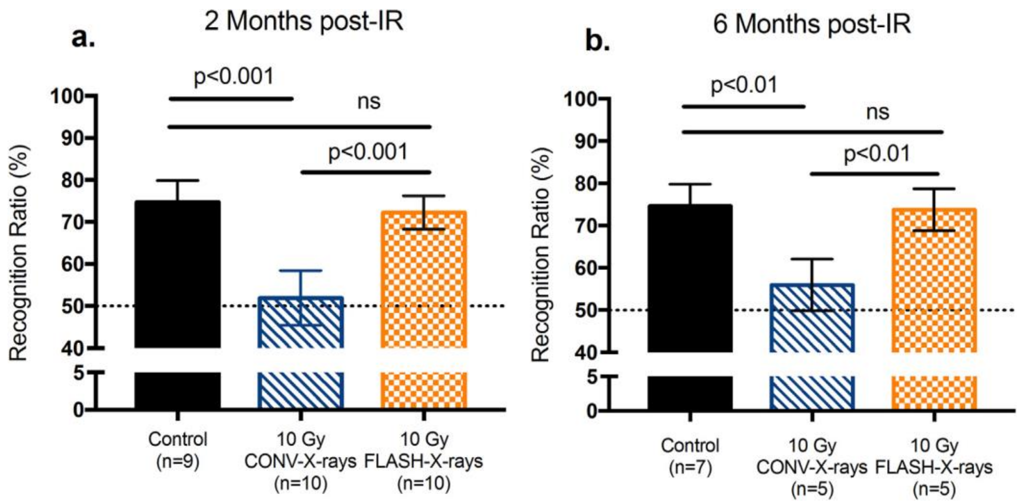
Ref: Stefan, B., et al. (January 01, 2020). Technical advances in x-ray microbeam radiation therapy. *65,* 2.)

Name	Value	Units
Energy	25	keV
Total flux	10^{13}	ph/s
Bandwidth	3.6	%
Source size (at IP)	70	µm
Divergence	1.5	mrad

[1] Jacquet, M., & Suortti, P. (January 01, 2015). Radiation therapy at compact Compton sources. *Physica Medica, 31,* 6, 596-600.
[2] Dombrowsky, A. C., et al. (2019). A proof of principle experiment for microbeam radiation therapy at the Munich compact light source. (Radiation and environmental biophysics.)
[3] Stefan, B., et al. (January 01, 2020). Technical advances in x-ray microbeam radiation therapy. *65,* 2.)

FLASH therapy

- FLASH-RT applies high intensity doses in a much smaller timeframe than CONV-RT, typically 100 Gy/s compared to 1 Gy/s in conventional therapy.
- Successful experiments have been performed at ESRF with 102 keV [2].
- Would normally require **6-10 MeV** X rays for a good depth penetration [1].
- Benefit from maximal photon flux [2].
- Authors of the ESRF paper suggested the use of ICS sources with high brilliance and dose rates over 100 Gy/s (3.6×10^{11} μSv/h) [2].



Ref: Montay-Gruel, P., et al. (December 01, 2018). X-rays can trigger the FLASH effect: Ultra-high dose-rate synchrotron light source prevents normal brain injury after whole brain irradiation in mice. *Radiotherapy and Oncology, 129,* 3, 582-588.

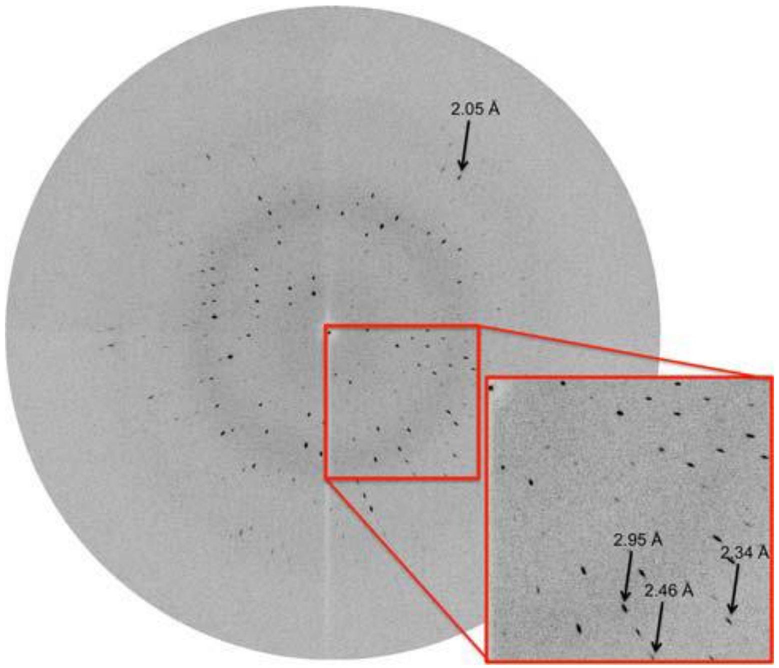
Name	Value	Units
Energy	102	keV
Total dose	10	Gy
Total flux	1.33×10^{14}	Ph/s
Source size (at IP)	50	μm

[1] Wilson, J. D., Hammond, E. M., Higgins, G. S., Petersson, K., & Petersson, K. (February 25, 2020). Ultra-High Dose Rate (FLASH) Radiotherapy: Silver Bullet or Fool's Gold?. *Frontiers in Oncology, 10.*
[2] Montay-Gruel, P., et al. (December 01, 2018). X-rays can trigger the FLASH effect: Ultra-high dose-rate synchrotron light source prevents normal brain injury after whole brain irradiation in mice. *Radiotherapy and Oncology, 129,* 3, 582-588.
[3] Bourhis, J., et al. (January 01, 2019). Clinical translation of FLASH radiotherapy: Why and how?. *Radiotherapy and Oncology, 139,* 11-17.

Protein crystallography

Parameter	Present	Planned	Notes
Total flux	$\sim 10^{11}$ ph/s	$\sim 10^{13}$ ph/s	Full bandwidth
Total flux (output BW)	$\sim 10^{9}$ ph/s	$\sim 10^{11}$ ph/s	3–4% bandwidth
Flux on crystal	$\sim 10^{7}$ ph/s	$\sim 10^{9-10}$ ph/s	0.1–1% bandwidth
Source spot size	50 μm rms	30 μm rms	Also image size for 1:1 optics
Source divergence	~2.5 mrad	~2.0 mrad	
X-ray energy range	10–20 keV	7–35 keV	Tunable

- Using x ray diffraction, can determine structure of protein crystals [1].
- Studies done with Lyncean Technologies' CLS [1].
- "The synchrotron imaging community has been hoping for a CLS-like source for more than 20 years" [1].
- X ray diffraction is also used in the pharmaceutical industry to determine the crystal structure of drug substances [2].

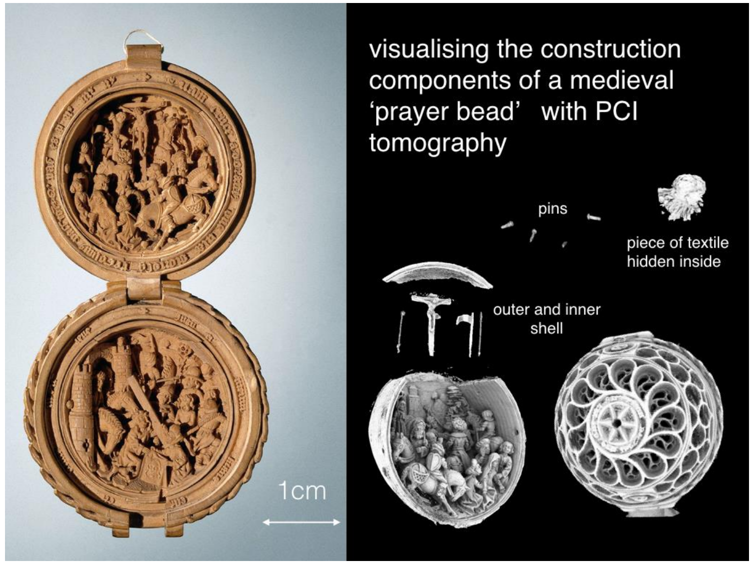


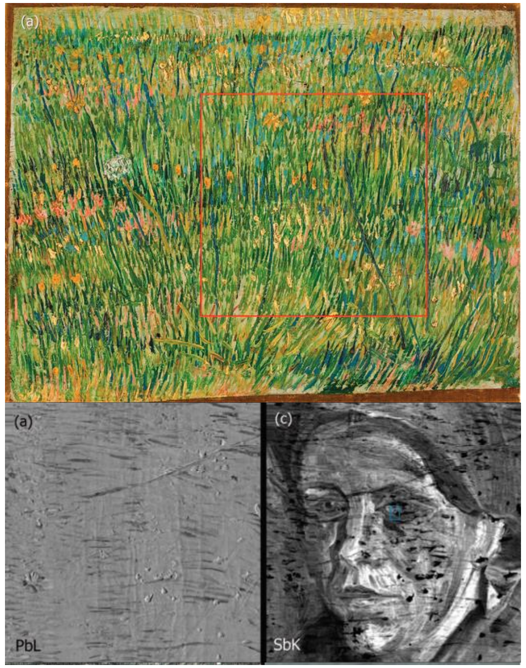
Ref: Abendroth, J., et al. (January 01, 2010). X-ray structure determination of the glycine cleavage system protein H of Mycobacterium tuberculosis using an inverse Compton synchrotron X-ray source. Journal of Structural and Functional Genomics, 11, 1, 91-100

[1] Abendroth, J., et al. (January 01, 2010). X-ray structure determination of the glycine cleavage system protein H of Mycobacterium tuberculosis using an inverse Compton synchrotron X-ray source. Journal of Structural and Functional Genomics, 11, 1, 91-100
[2] Byrn, S. R., Zografi, G., & Chen, X. (2017). *Solid state properties of pharmaceutical materials*.

Cultural heritage

- ICS sources could also be used to conduct cultural heritage studies in museums.
- Required x ray parameters for various analysis techniques can be achieved at ThomX [1].
- x ray fluorescence was used to discover a hidden Van Gogh painting [2].
- High intensity x ray beams allow for decimeter-sized areas to be scanned [2].





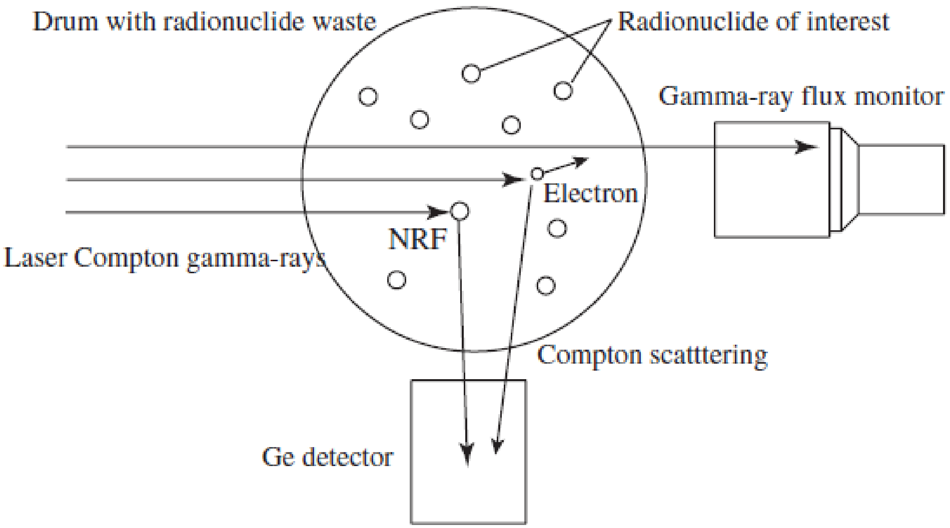
Requirements table for the analysis techniques used in heritage studies.

	XRF	XRD	XANES	Tomography	Edge enhancement	Phase contrast	Magnification
Energy range [keV]	6.5–92	10–92	6.5–92	20–100	7–100	10–30	10–100
$\Delta E/E$	1–3%	3–10%	5–10%	3% bw	3–10%	3% bw	3% bw
Source size				10–100 μm	10–100 μm	Very small	Very small
Size on the object	20 μm	20 μm	20 μm	10–50 cm	50 cm	50 cm	1–50 mm
Flux on the object [ph/s]	10^9–10^{10}	10^9 ph/s	10^7 ph/s	10^{11}	10^9	10^{11}	10^{11}
Acquisition time	1–60 s	1–300 s	2000 s				
Coherence				No	No	Yes	No

[1] Walter, P., et al.(September 01, 2009). A new high quality X-ray source for Cultural Heritage. *Comptes Rendus - Physique, 10*, 7, 676-690.
[2] Dik, J., et al. (August 01, 2008). Visualization of a Lost Painting by Vincent van Gogh Using Synchrotron Radiation Based X-ray Fluorescence Elemental Mapping. *Analytical Chemistry, 80*, 16, 6436-6442.

Nuclear waste management

- Proposed nondestructive assay system for radioactive nuclides [1].
- No current ICS source reaches the required energies, so the authors proposed one of their own design.
- Their source would have used an ERL, a high-power fiber laser and a laser supercavity.



A schematic view of nuclear resonance fluorescence measurement

Name	Value	Units
Energy	1000-5000	keV
Flux	3.1×10^{13}	ph/s
Bandwidth	0.2	%
Source size (at IP)	35	µm

[1] Ryoichi, H., et al. (January 01, 2008). Proposal of nondestructive radionuclide assay using a high-flux gamma-ray source and nuclear resonance fluorescence. *Journal of Nuclear Science and Technology, 45,* 5, 441-451.

Flux

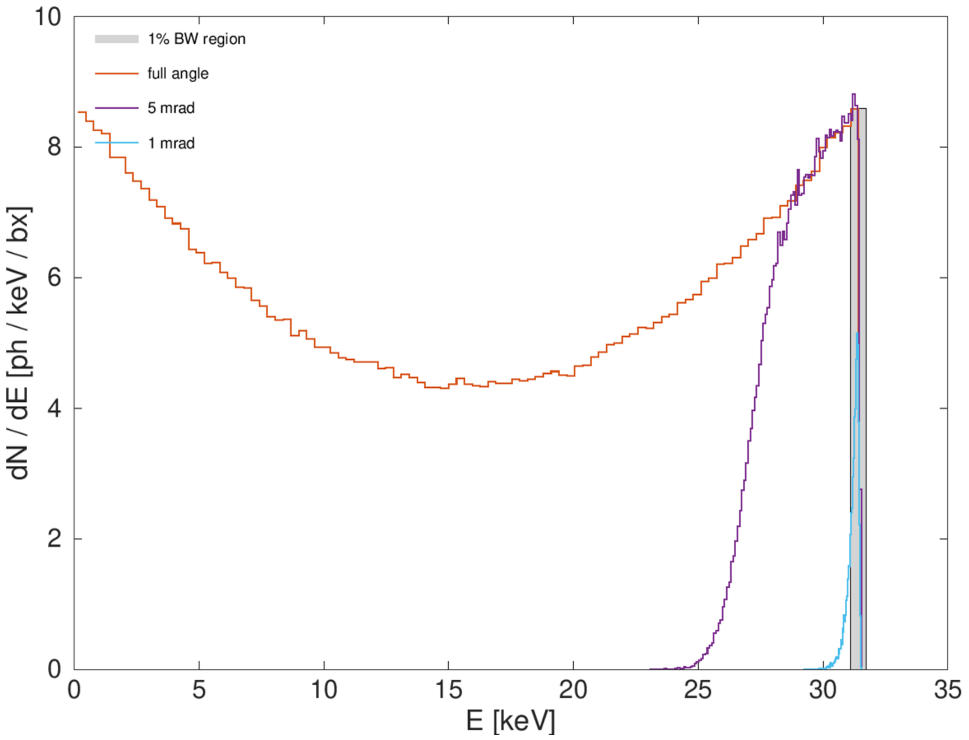
- Flux = number of photons per second
- The total number of scattered photons N_γ for a crossing angle ϕ after a collision between an electron bunch of N_e electrons and a laser pulse of N_laser photons is [1]

$$N_\gamma = \sigma_\mathrm{c} \frac{N_\mathrm{e} N_\mathrm{laser} \cos(\phi/2)}{2\pi\sigma_y \sqrt{\sigma_x^2 \cos^2(\phi/2) + \sigma_z^2 \sin^2(\phi/2)}} \quad \text{[unitless]}$$

- Assuming incident laser approximates to a plane wave, the flux $\mathcal{F}$ within a 0.1% bandwidth at the Compton edge is

$$\mathcal{F} \simeq 1.5 \times 10^{-3} \dot{N}_\gamma \quad \text{[ph/s]}$$

where $\dot{N}_\gamma = N_\gamma f$ is the total uncollimated flux and f is the collision repetition rate.



- $\sigma_i^2 = \sigma_{\mathrm{electron},i}^2 + \sigma_{\mathrm{laser},i}^2$ is the convoluted spot size of the electron and laser beam in each direction ($i = x, y, z$) at the interaction point (IP)
- σ_c is the Compton scattering cross section
- For typical lasers with $\lambda_\mathrm{laser} = 1064$ nm, can approximate σ_c with the Thomson cross section, $\sigma_\mathrm{c} \simeq \sigma_\mathrm{T}$

[1] T. Suzuki, General formulas of luminosity for various types of colliding beam machines, Technical Report, National Laboratory for High Energy Physics, 1976, https://inspirehep.net/files/56200f5110f34e07afe6e25af9f95528.

Bandwidth

- For head-on collisions through a small aperture for regime where recoil is negligible,

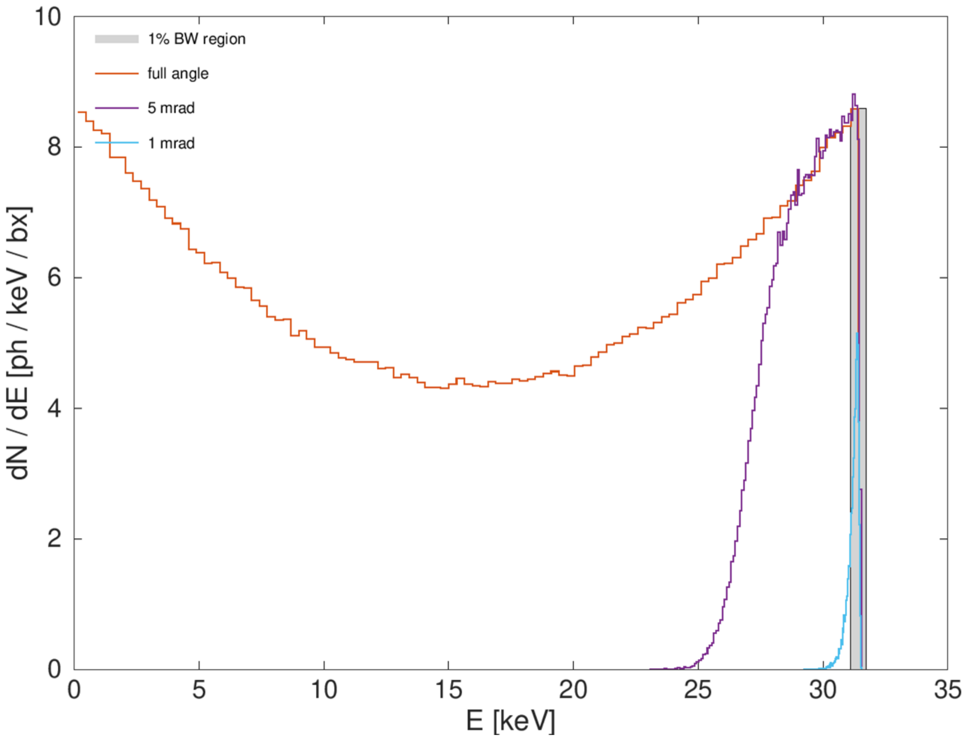
$$\frac{\sigma_{E_\gamma}}{E_\gamma} = \sqrt{\left(\frac{\sigma_{E_\theta}}{E_\theta}\right)^2 + \left(2\frac{\sigma_{E_e}}{E_e}\right)^2 + \left(\frac{\sigma_{E_l}}{E_l}\right)^2 + \left(\frac{\sigma_{E_\epsilon}}{E_\epsilon}\right)^2}$$

- Contribution from small aperture,

$$\frac{\sigma_{E_\theta}}{E_\theta} = \frac{1}{\sqrt{12}}\frac{\gamma^2\theta^2}{1+\gamma^2\theta^2/2}$$

- $\frac{\sigma_{E_e}}{E_e}, \frac{\sigma_{E_l}}{E_l}$ are the relative energy spreads of electron and laser beams
- Contribution from beam emittance through small aperture,

$$\frac{\sigma_{E_\epsilon}}{E_\epsilon} = \frac{2\gamma^2\epsilon}{\beta}$$



[1] Deitrick, K. E., et al.. (August 24, 2018). High-brilliance, high-flux compact inverse Compton light source. *Physical Review Accelerators and Beams, 21,* 8.)

Brilliance

- Spectral brilliance is the density of photons in the six-dimensional space containing the beam [1]

$$\mathcal{B} = \frac{\mathcal{F}_{0.1\%}}{4\pi^2 \sigma_{\gamma,x}\sigma_{\gamma,x'}\sigma_{\gamma,y}\sigma_{\gamma,y'}}$$ [ph/(s mm^2 mrad^2 0.1% BW)]

- In a nondiffraction limited beam where $\sigma_{\gamma,x'} \approx \sqrt{\epsilon_x/\beta_x}$,

$$\mathcal{B} = \frac{\mathcal{F}_{0.1\%}}{4\pi^2 \sigma_{\gamma,x}\sqrt{\epsilon_x/\beta_x}\sigma_{\gamma,y}\sqrt{\epsilon_y/\beta_y}}$$

- For a compact source, $\sigma_{\gamma,x} = \sigma_x = \sqrt{\beta_x \epsilon_x}$ and

$$\mathcal{B} \approx \frac{\gamma^2 \mathcal{F}_{0.1\%}}{4\pi^2 \epsilon_x^N \epsilon_y^N}$$

- The peak brilliance is the average brilliance $\mathcal{B}$ normalised by the electron bunch length τ [2],

$$\hat{\mathcal{B}} = \frac{2.355^2}{2\pi}\frac{\mathcal{B}}{f\tau}$$ [ph/(s mm^2 mrad^2 0.1% BW)]

- $\sigma_{i'}$ is the beam divergence [rad]
- ϵ_i is the electron beam emittance [m rad]
- β_i is the electron beta function at the IP [m]
- ϵ_i^N is the normalised emittance [m rad]
- $\epsilon_i^N = \beta\gamma\epsilon_i$, where $\beta = v/c$ and γ is the Lorentz factor

Note: In US, brightness, and in rest of the world, brilliance.

[1] Thomas Jefferson National Accelerator Facility (U.S.), United States., & United States. (2011). *Compton Sources of Electromagnetic Radiation*. Washington, D.C: United States. Dept. of Energy. Office of Science.
[2] Q. Shen, CHESS TM 01-002, http://erl.chess.cornell.edu/Papers/Papers.htm