First study of an ICS source based on CompactLight technology

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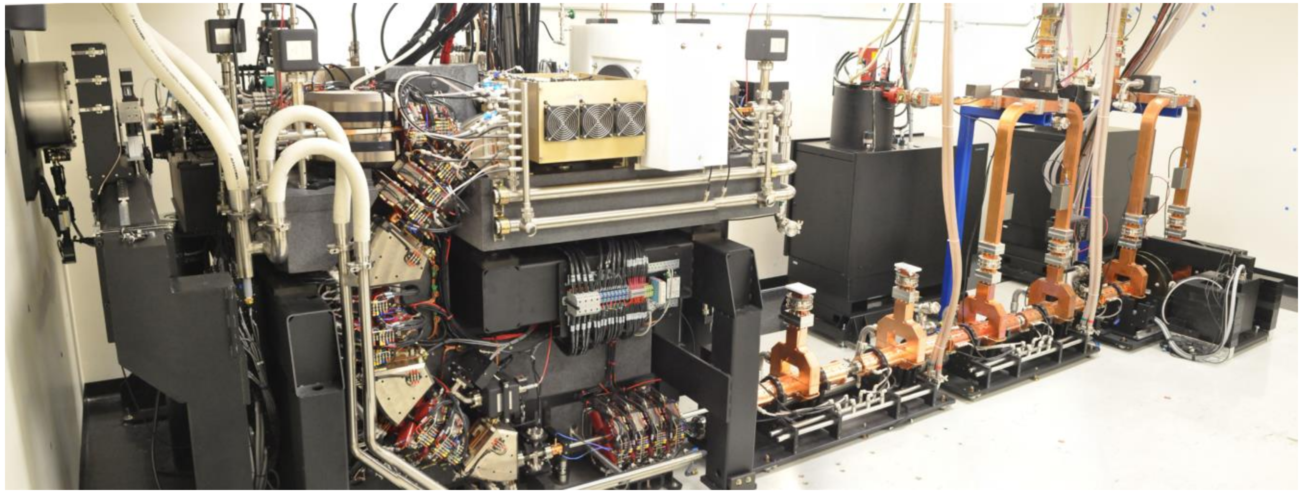
Contents

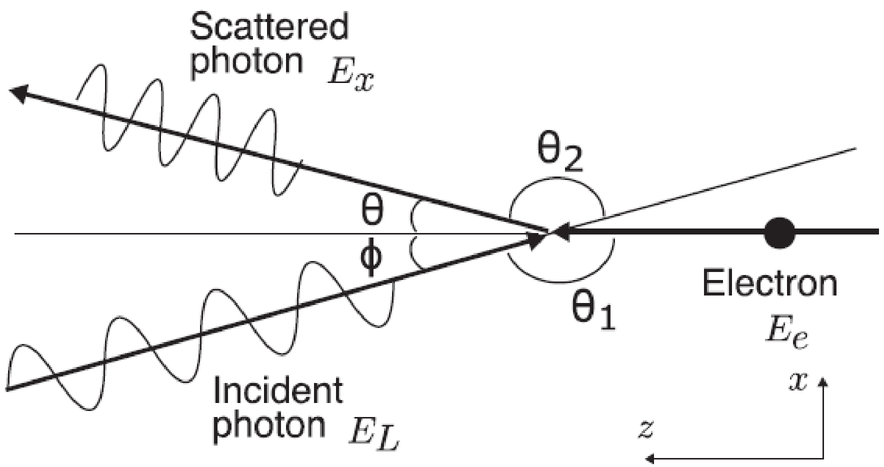
I. Introduction

Inverse Compton Scattering (ICS)

ICS = Scattering of a low energy photon from a relativistic electron resulting in a high energy x-ray

- ICS first described by Feenberg and Primakoff in 1948 [1].
- Several existing ICS sources: ThomX (France), TTX (China), MuCLS (Germany), etc.
- Applications include cancer therapy [2], X-ray imaging [3], cultural heritage [4], and nuclear waste management [5].

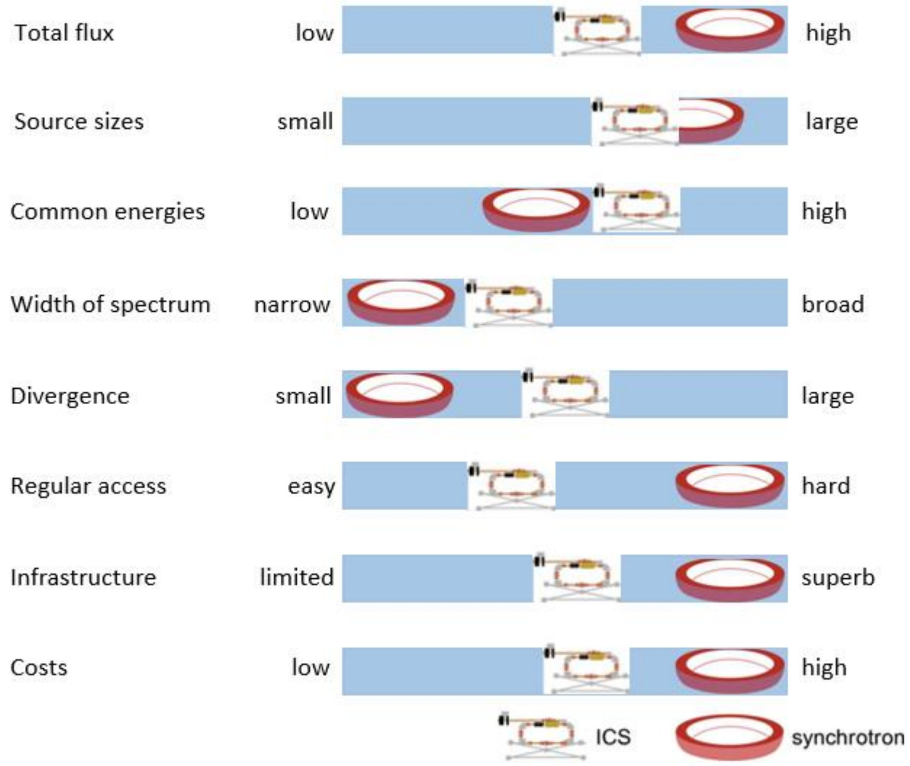




[1] Feenberg, E., & Primakoff, H. (March 01, 1948). Interaction of Cosmic-Ray Primaries with Sunlight and Starlight. Physical Review, 73, 5, 449-469.
[2] Montay-Gruel, P., et al. (December 01, 2018). X-rays can trigger the FLASH effect: Ultra-high dose-rate synchrotron light source prevents normal brain injury after whole brain irradiation in mice. Radiotherapy and Oncology, 129, 3, 582-588.
[3] Gradl, R., et al. (2017). Propagation-based Phase-Contrast X-ray Imaging at a Compact Light Source. (Scientific reports.)
[4] Walter, P., et al. (September 01, 2009). A new high quality X-ray source for Cultural Heritage. Comptes Rendus - Physique, 10, 7, 676-690.
[5] Hajima, R., et al. (May 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.

Synchrotrons vs. ICS sources

- Synchrotrons (ESRF, APS, etc.) currently provide the highest energy x-rays [1], however…
- Large scale, expensive structures with limited access time and many constraints to experiments.
- Improvements in high power lasers have led to increasing developments of compact Compton X-ray sources.
- ICS sources replace synchrotron's magnet-based undulators and wigglers with a laser.
- Covering areas of ~100 m^2, ICS sources achieve high intensity and quality x-ray beams with tunable energy comparable to synchrotron sources.
- These devices could be used in laboratories and clinical environments.



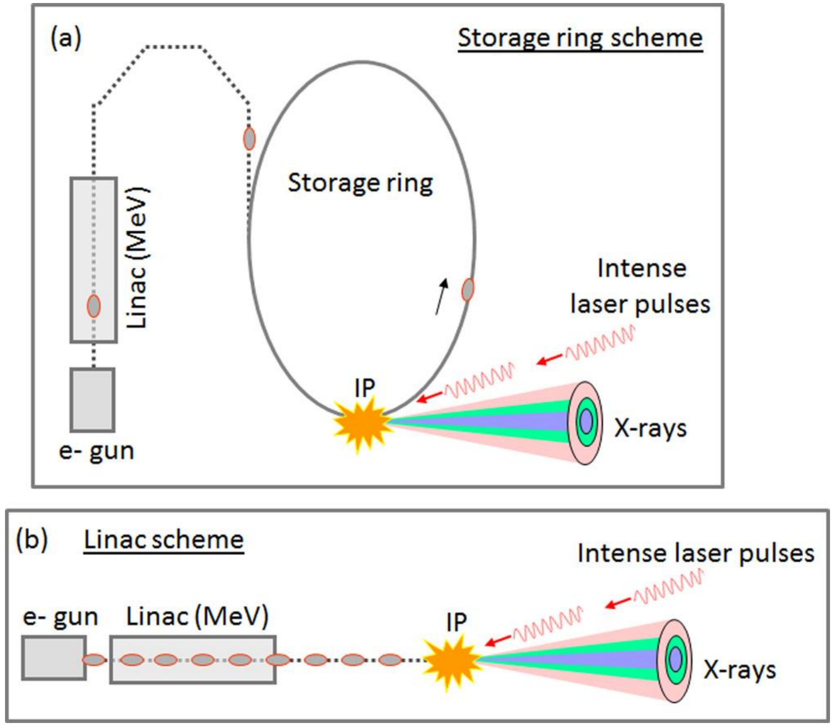
Ref: Günther, et al. (September 01, 2020). The versatile X-ray beamline of the Munich Compact Light Source: design, instrumentation and applications. *Journal of Synchrotron Radiation, 27,* 5, 1395-1414

Note: The pictured ICS corresponds to the MuCLS storage ring, while the pictured synchrotron corresponds to the ESRF.

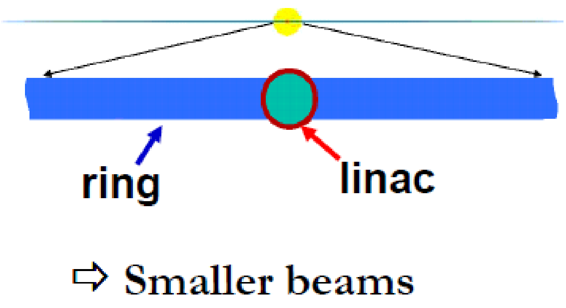
[1] Jacquet, M. (January 01, 2016). Potential of compact Compton sources in the medical field. Physica Medica, 32, 12, 1790-1794.

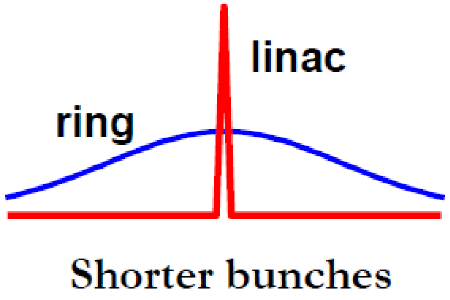
Storage Ring vs. Linac

- In storage rings (SR), a particle beam with high average current may be kept circulating for hours [1]. The electron beam is recycled, and RF cavities replace energy lost by particles through synchrotron radiation.
- SR sources: ThomX (France), NESTOR (Ukraine), TTX (China), MuCLS (Germany).
- Linear accelerators (linacs) provide a single beam [1]. They have lower emittance beams, and are easier to align, which enables a faster x-ray energy tuning. Linacs also achieve higher brilliance than storage rings, however extensive radioprotection is required. [2]
- Linac sources: CXLS (US), CXFEL (US), STAR (Italy).
- Energy recovery linac (ERL) is a proposed upgrade on the linac design. [3]
- ERL's only reuse the electron beam's energy. ERL sources seek to combine the best aspects of both storage rings and linacs: higher quality beams than storage rings with a higher efficiency than linacs. However, they require SC-RF.
- Examples of ERL sources: CBETA (US), cERL (Japan), ALICE (UK).



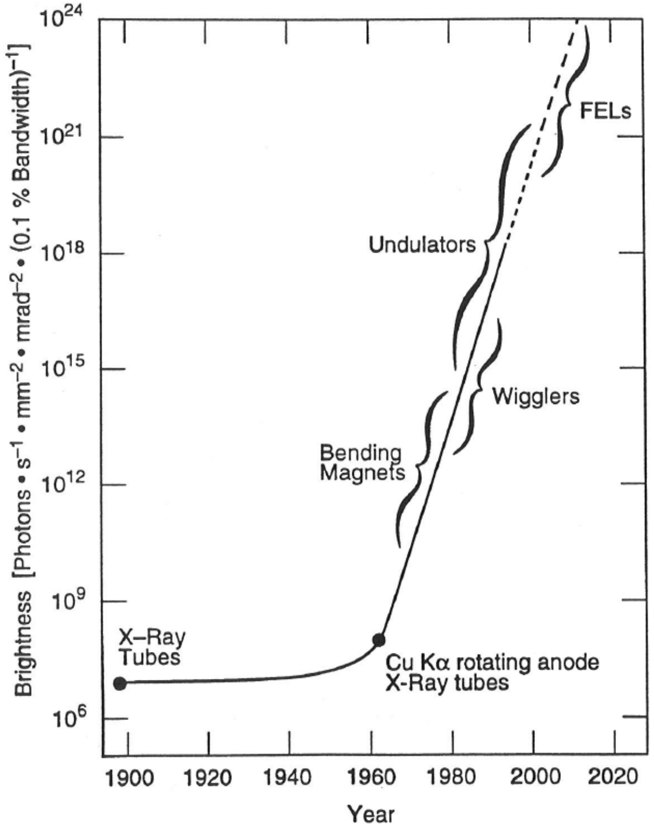
Ref: Jacquet, M. (January 01, 2016). Potential of compact Compton sources in the medical field. Physica Medica, 32, 12, 1790-1794.



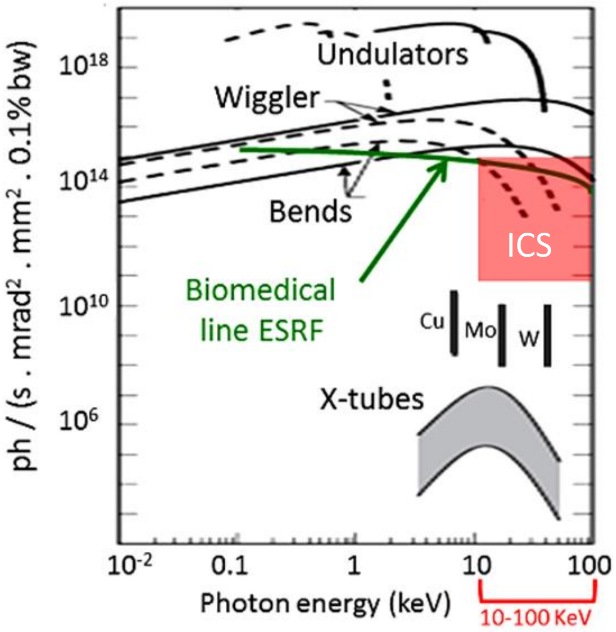


[1] Thomas Jefferson National Accelerator Facility (U.S.), United States., Geoffrey, K., & USDOE Office of Energy Research (ER) (US). (2003). *Recirculated and Energy Recovered Linacs*. Newport News, Va: Thomas Jefferson National Accelerator Facility.
[2] Jacquet, M. (July 15, 2014). High intensity compact Compton X-ray sources: Challenges and potential of applications. *Nuclear Inst. and Methods in Physics Research, B, 331,* 1-5.
[3] Gruner, S. M., Bilderback, D., Bazarov, I., Finkelstein, K., Krafft, G., Merminga, L., Padamsee, H., ... SRI 2001, Madison, WI (US), 08/22/2001--08/24/2001; Other Information: PBD: 1 Mar 2002. (2002). *Energy recovery linacs as synchrotron radiation sources*.

History



- First ICS experiments were done at already existing electron storage rings such as Adone, Brookhaven and ESRF. Experiments were continued I the 1980's with storage rings, where intracavity FEL beams were collided with electrons. Although MeV x ray energies were reached, total flux remained under 10^6 ph/s. Higher flux was achieved by implementing high-finesse, high average power optical cavities, typically Fabry-Pérot cavities. [1]
- A Fabry-Pérot cavity stores laser photons matching a resonance condition. It consists of two perfectly aligned high-reflectivity mirrors. The cavity can store an optical power several orders of magnitude larger than the input power. [2]
- Linacs are a popular alternative to storage rings. In 2000, Jefferson Lab tested this new design in combination with an FEL laser. Since then, many more linac based ICS sources have been proposed. [1]
- Energy recovery linac (ERL) sources are among the most promising designs currently. First proposed in 2002.[1]



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

[1] Thomas Jefferson National Accelerator Facility (U.S.). (2011). *Compton Sources of Electromagnetic Radiation*. Washington, D.C: United States. Dept. of Energy. Office of Science.
[2] Toyokawa, H. & Yamada, Kawakatsu & Ohgaki, H. & Hayashi, Shusuke & Kii, Toshiteru & Yamazaki, Testuo & Goko, Shinji. (2005). Long-Axis Fabry-Pérot Cavity for Intense Laser-Compton Photon Beam. Japanese Journal of Applied Physics. 44. 7671-. 10.1143/JJAP.44.7671.

Flux

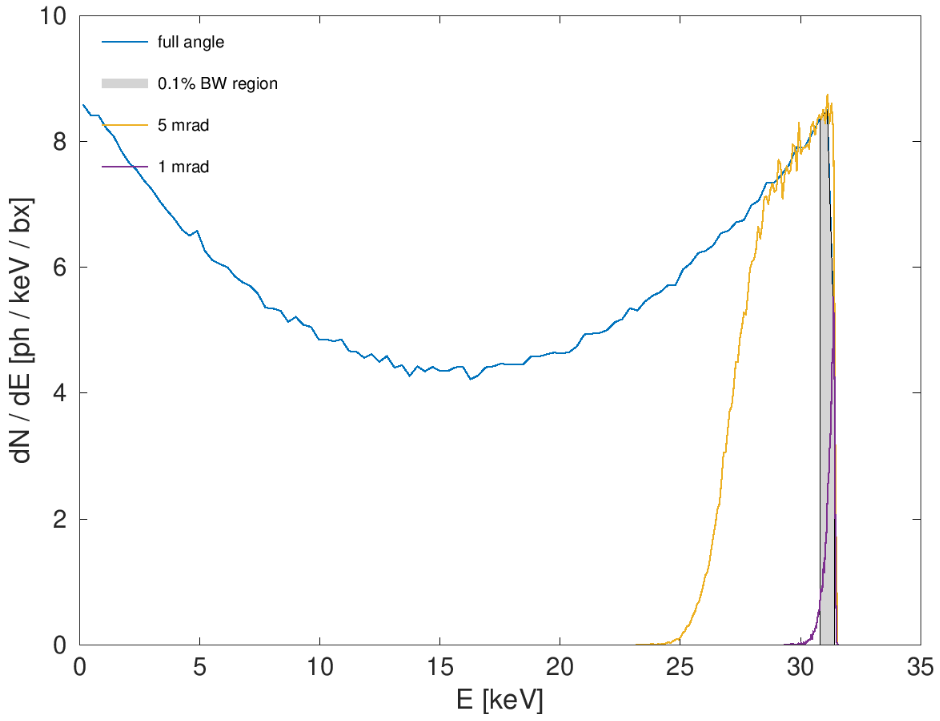
- Flux = number of photons per second
- The total number of scattered photons N_γ for a crossing angle ϕ after a collision between an electron bunch of N_e electrons and a laser pulse of N_{laser} photons is

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

- 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 frequency.



- $\sigma_i^2 = \sigma_{electron,i}^2 + \sigma_{laser,i}^2$ 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 $\lambda_{laser} = 1064$ nm, can approximate σ_c with the Thomson cross section, $\sigma_c \simeq \sigma_T$

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,

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

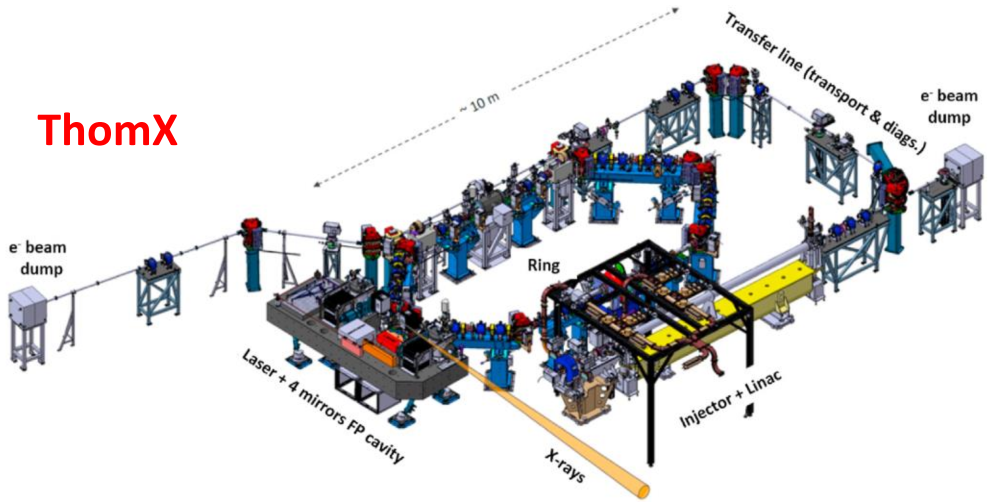
- $\sigma_{i'}$ is the beam divergence [rad]
- ϵ_i is the electron beam emittance [m rad]
- β_i is the electron beta function at the IP [m]
- ϵ_i^N is the normalised emittance [m rad]
- $\epsilon_i^N = \beta\gamma\epsilon_i$, where $\beta = v/c$ and γ is the Lorentz factor

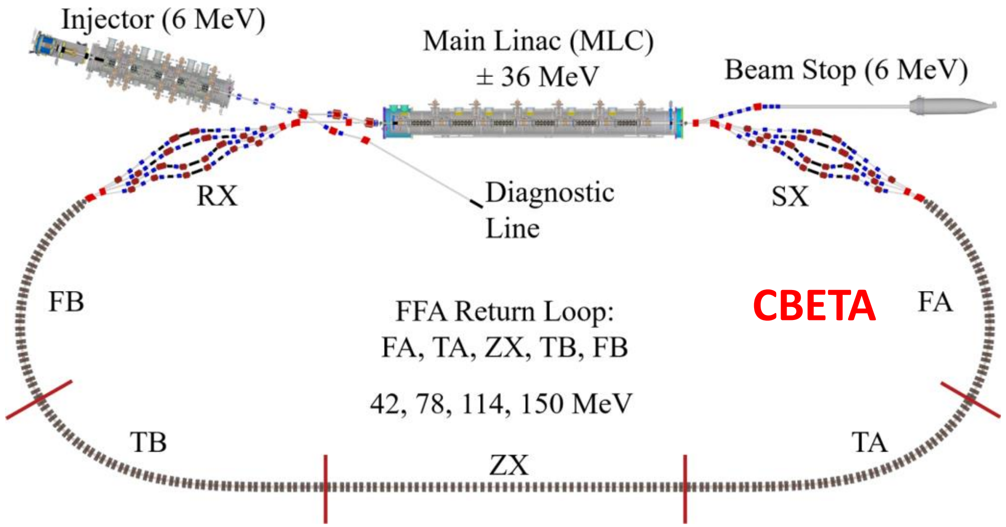
Note: In US, brightness, and in rest of the world, brilliance.

[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.

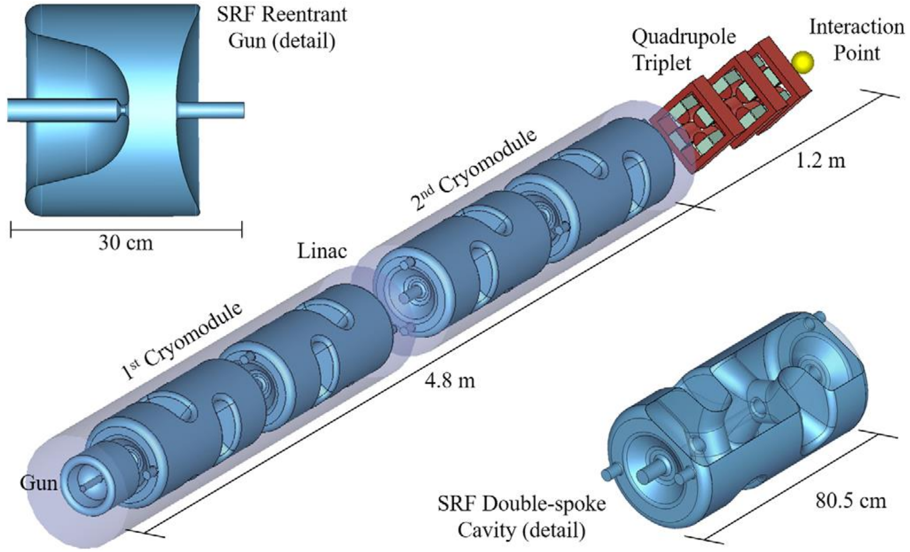
ICS sources used for RF-Track simulation

ThomX

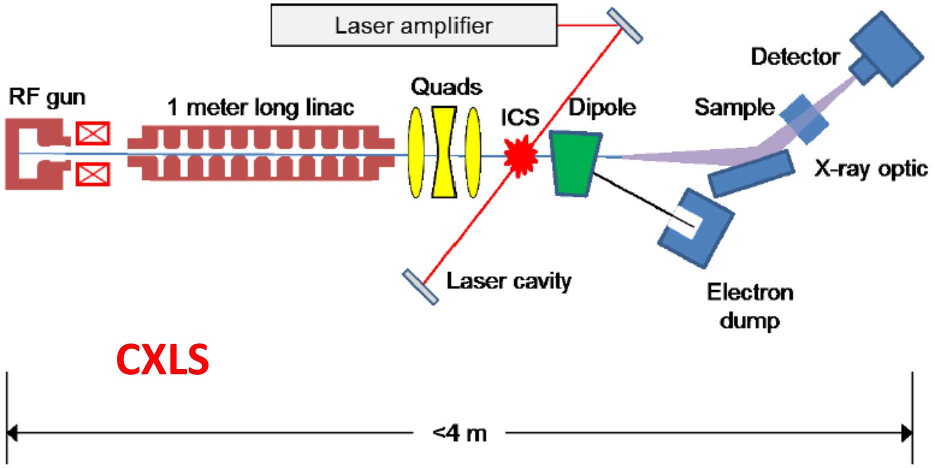




CBETA



ODU CLS



CXLS

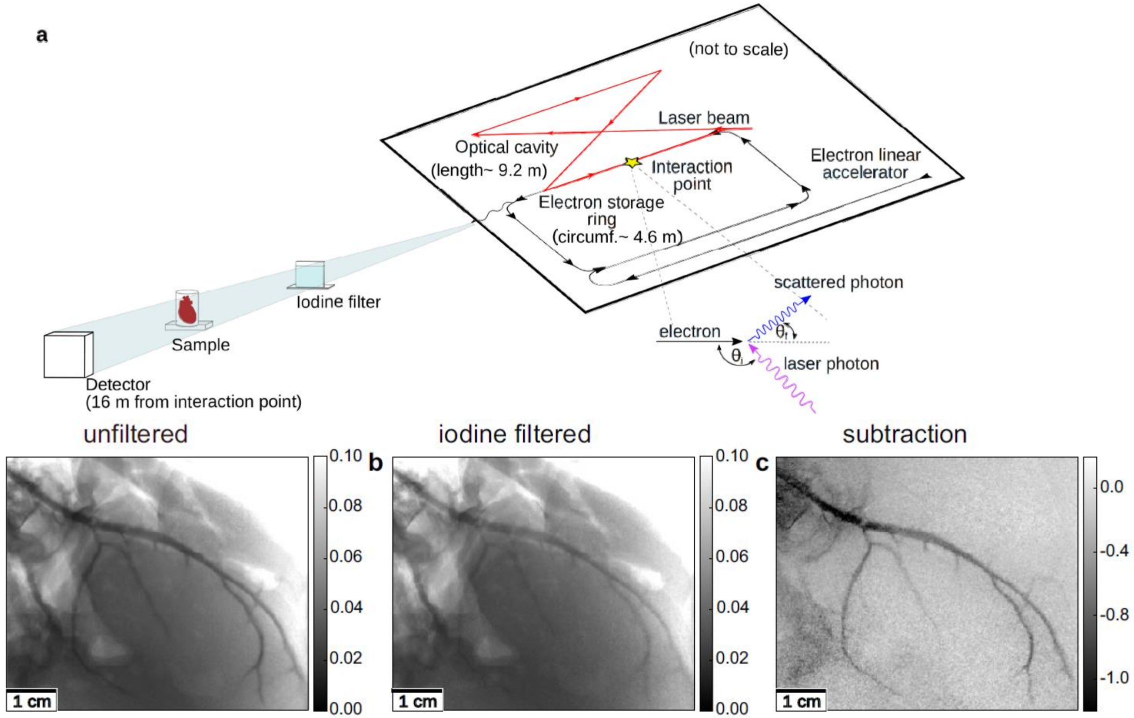
Table of parameters for all simulated ICS sources

	ThomX	CBETA	ODU CLS	CXLS	
Parameter	Quantity				Units
Beta function (at the IP), β^*	0.1	10	5	1.5	mm
Crossing angle, ϕ	2	5	2	2.86	deg
Bunch repetition frequency, f	17.8×10^3	162.5×10^3	100×10^3	1	kHz
Nb of bunches per train	1	1	1	100	
Effective repetition frequency, f	17.8×10^3	162.5×10^3	100×10^3	100	kHz
Electron kinetic energy, E_{el}	50-70	42, 78, 114, 150	25	8-40	MeV
Energy spread, $\delta E/E$	3	0.5	0.45	0.8	‰
Bunch length, σ_z	10-20	3.33	3	0.5	ps
Bunch charge, Q_{pc}	50-100	32	10	100	pC
Normalised emittance, ϵ_x^N, ϵ_y^N	2-9	0.3, 0.3	0.1, 0.1	0.17, 0.17	mm mrad
Pulse energy	28	0.062	10	100	mJ
Pulse length, τ	5	10	0.67	2	ps
Wavelength, λ	1030	1064	1000	515, 1030	nm
Laser spot size, w_0	35	25	3.2 / 12	3	μm
Total flux, $\mathcal{F}$	3×10^{13}	3×10^{10}	2×10^{13}	5×10^{11}	ph/s
Average brilliance, $\mathcal{B}$	3×10^{11}	9×10^{10}	4×10^{14}	2×10^{12}	ph/(s mm2 mrad2 0.1% BW)

II. Applications

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.

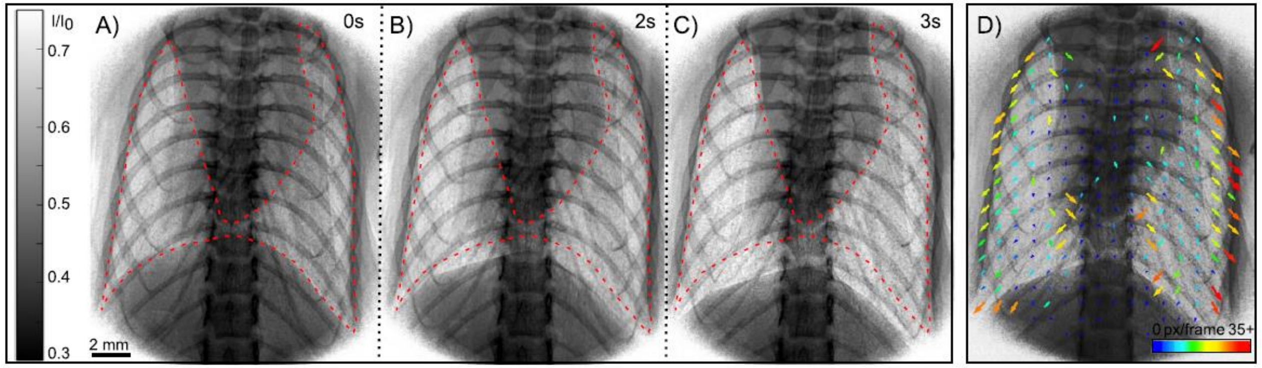


Ref: Kulpe, S., et al. (December 10, 2018). K-edge subtraction imaging for coronary angiography with a compact synchrotron X-ray source. *Plos One, 13,* 12.)

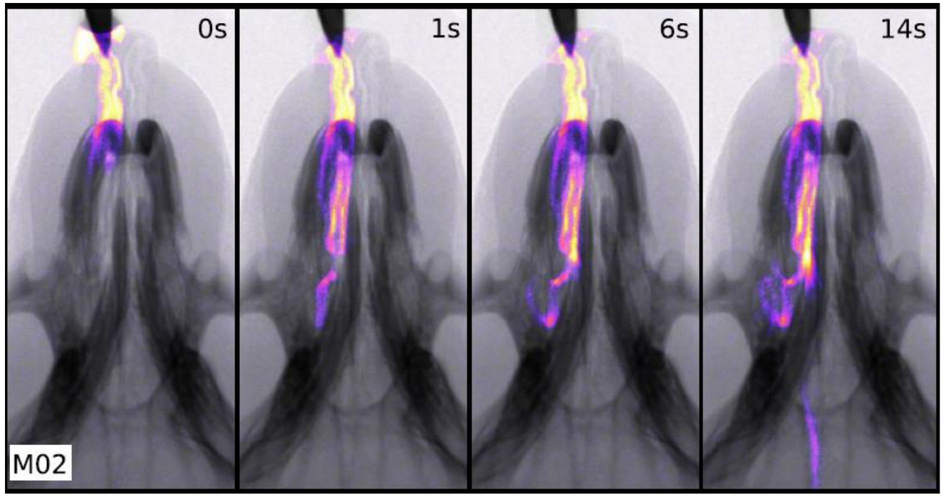
Name	Value	Units
Energy	33.7	keV
Total flux	3×10^{10}	ph/s
Bandwidth	4.5	%
Source size (at IP)	45	µm
Source size (at sample)	16	mm
Divergence	4	mrad

[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 spatialy 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.



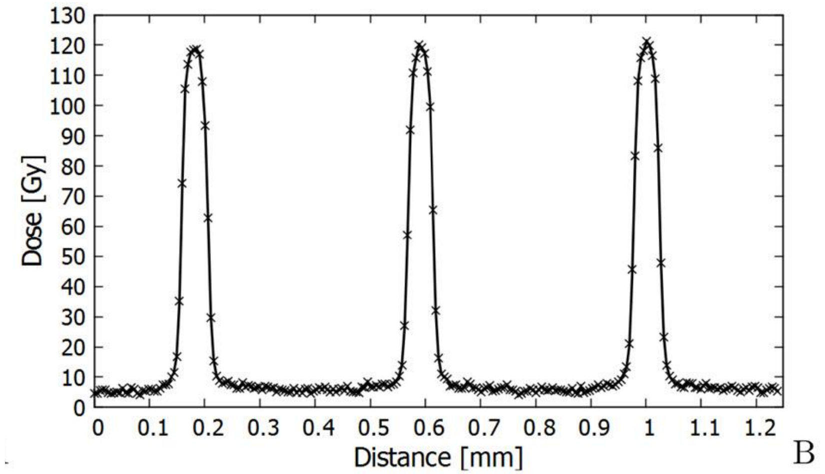
Ref: Gradl, R., et al., SpringerLink (Online service). (2018). In vivo Dynamic Phase-Contrast X-ray Imaging using a Compact Light Source. (Scientific reports.)

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., Dierolf, M., Günther, B., Hehn, L., Möller, W., Kutschke, D., Yang, L., ... 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]



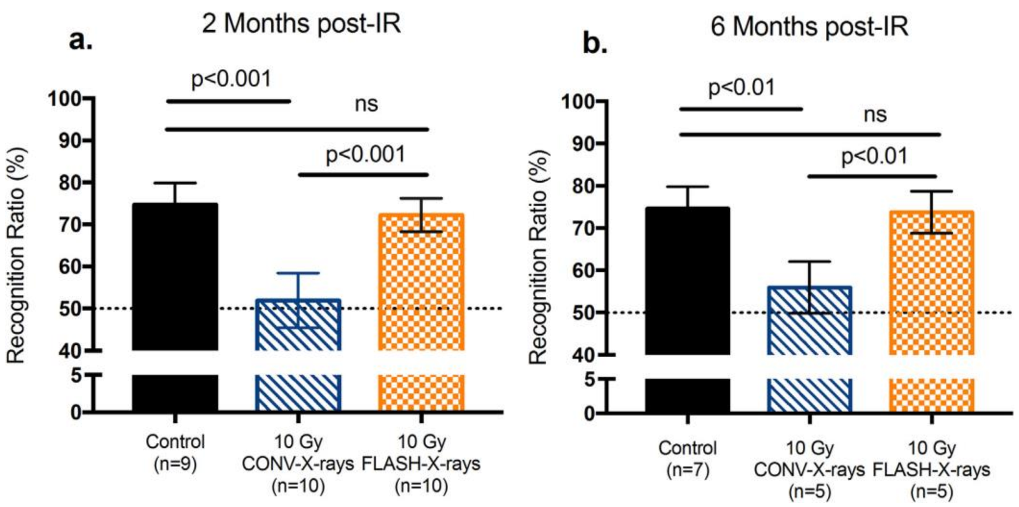
Ref: Stefan, B., et al. (January 01, 2020). Technical advances in x-ray microbeam radiation therapy. *65,* 2.)

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 225 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 [2].



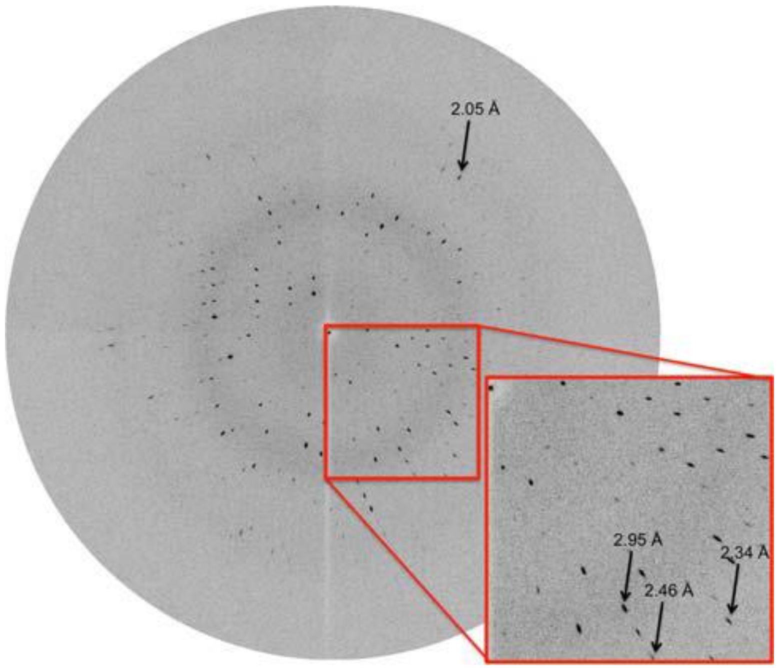
Ref: Montay-Gruel, P., et al. (December 01, 2018). X-rays can trigger the FLASH effect: Ultra-high dose-rate synchrotron light source prevents normal brain injury after whole brain irradiation in mice. *Radiotherapy and Oncology, 129,* 3, 582-588.

[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 crystallograpy

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	$\sim$2.5 mrad	$\sim$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].

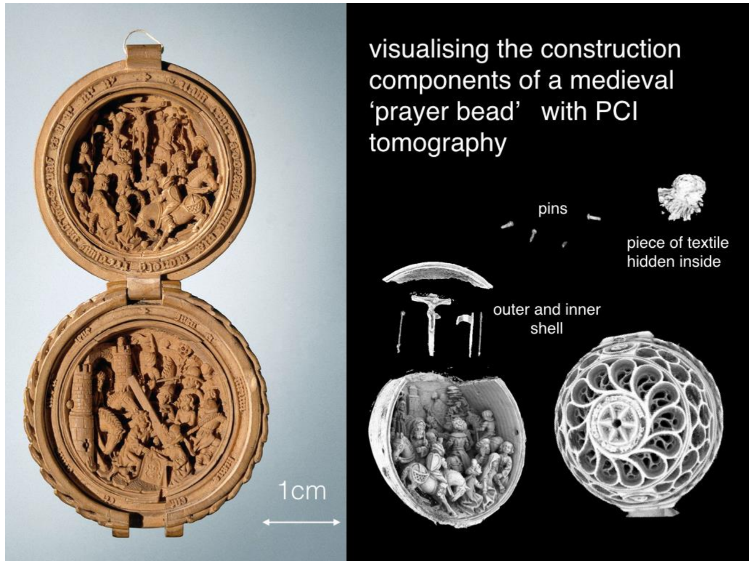


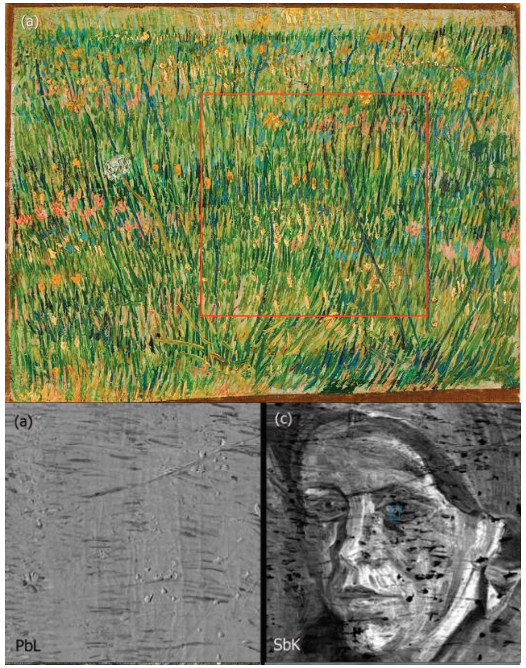
Ref: Abendroth, J., et al. (January 01, 2010). X-ray structure determination of the glycine cleavage system protein H of Mycobacterium tuberculosis using an inverse Compton synchrotron X-ray source. Journal of Structural and Functional Genomics, 11, 1, 91-100

[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].





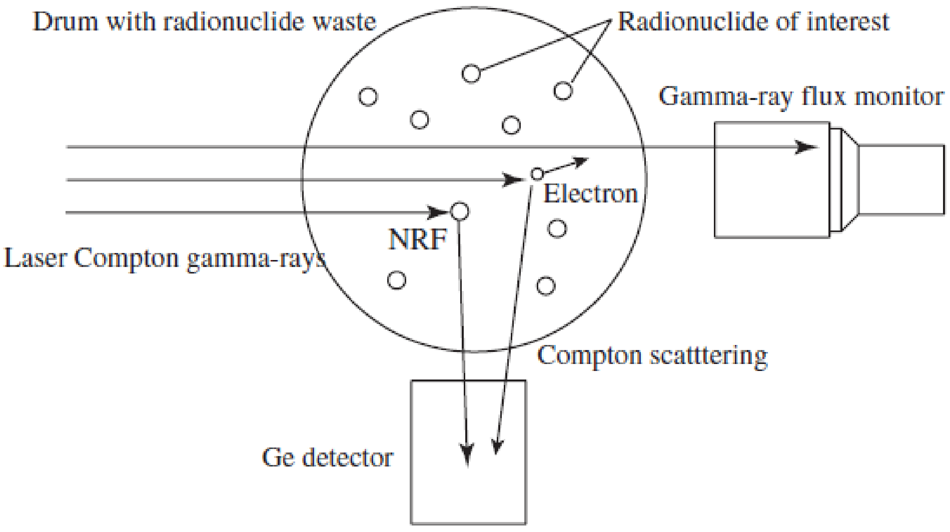
Requirements table for the analysis techniques used in heritage studies.

	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.

Summary - Applications

- Potential applications of ICS sources were presented.
- Most came up as extensions of previous synchrotron studies. 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 energy x rays, similarly to the ones created in synchrotron sources.
- Tomographies in particular have already been extensively studied, with proof of concept studies done at MuCLS.

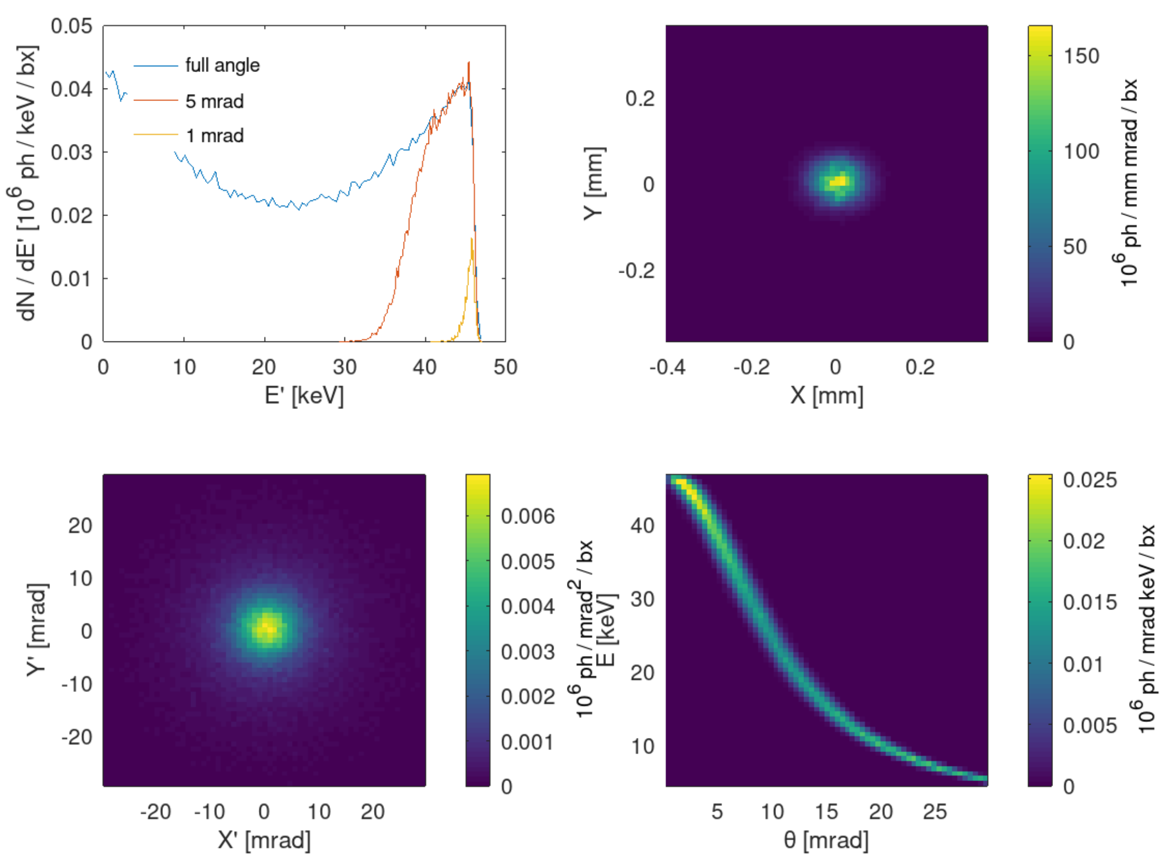
Name	E_{Xray} [keV]	$\mathcal{F}$ [ph/s]	BW [%]	σ_{Xray} (at IP) [μm]	σ_{Xray} (at sample) [mm]	Θ [mrad]
K-edge subtraction	33.7	3×10^{10}	4.5	6	16	4
Phase contrast imaging	25	2.4×10^{9}	4	39×45	16	4
Microbeam radiation therapy	25	10^{13}	3.6	70	4	1.5
Protein crystallography	7-35	$\sim 10^{13}$	1.4	30	30	2
XRF	6.5-92	3×10^{10}	1-3	20	20×10^{-3}	-
Nuclear waste management	1000-5000	2.2×10^{13}	0.2	35	-	-

III. Simulation of ICS sources

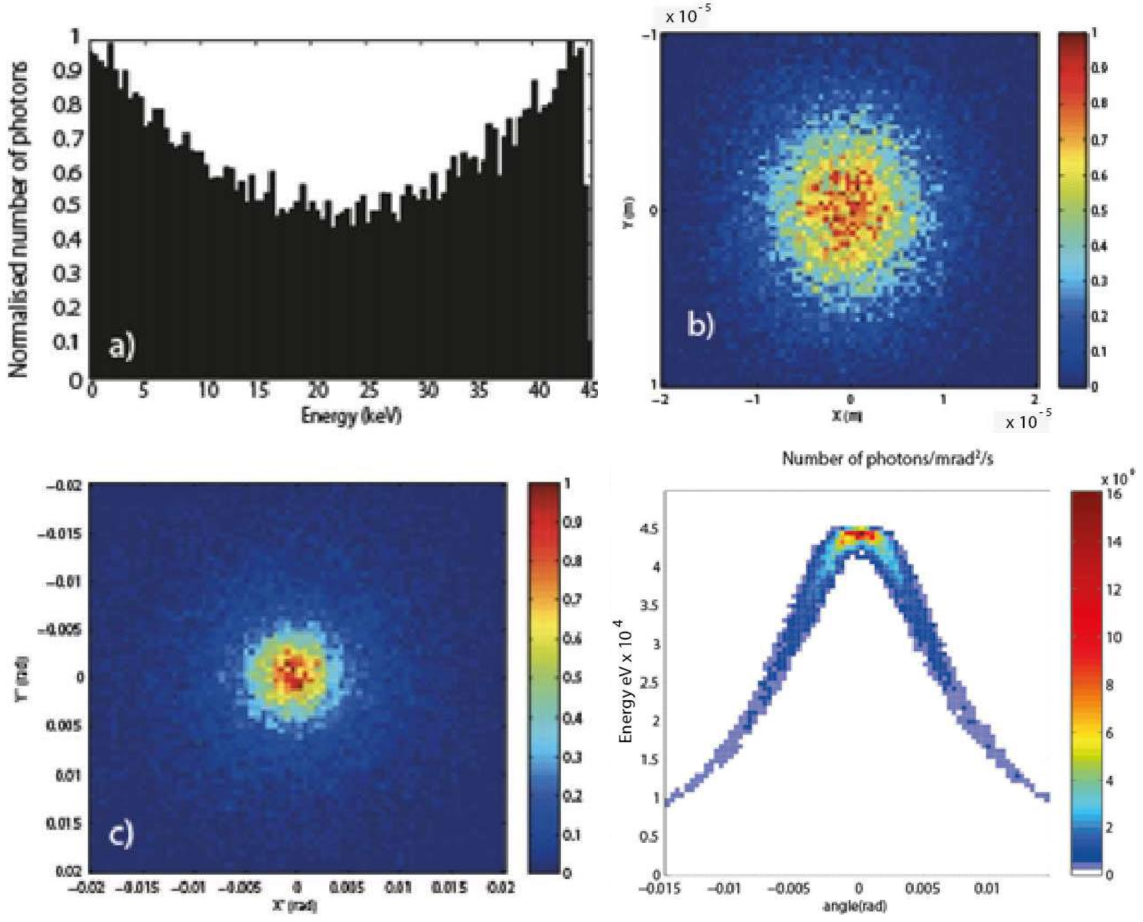
Method

[1] Andrea Latina, "RF-Track Reference Manual", CERN, Geneva, Switzerland, June 2020.
[2] Kevin Dupraz, et al. (December 01, 2020). The ThomX ICS source. *Physics Open, 5,* 100051.

- RF-Track, developed by Andrea Latina [1], was used to simulate four ICS sources at the laser and electron beam interaction point (IP).
- Sources were chosen based on their current status (existing, in development, or design-only) and performance: CXLS, CBETA, ThomX and ODU CLS.
- Flux and average brilliance were derived for each source and the results compared with references.
- Pictured are RF-Track simulation results for ThomX. Note the upper left plot, showing photon spectra at various collection angles. The Compton edge is at $\sim$ 45 keV, corresponding to the quoted 45 keV value [2].



ThomX: RF-Track



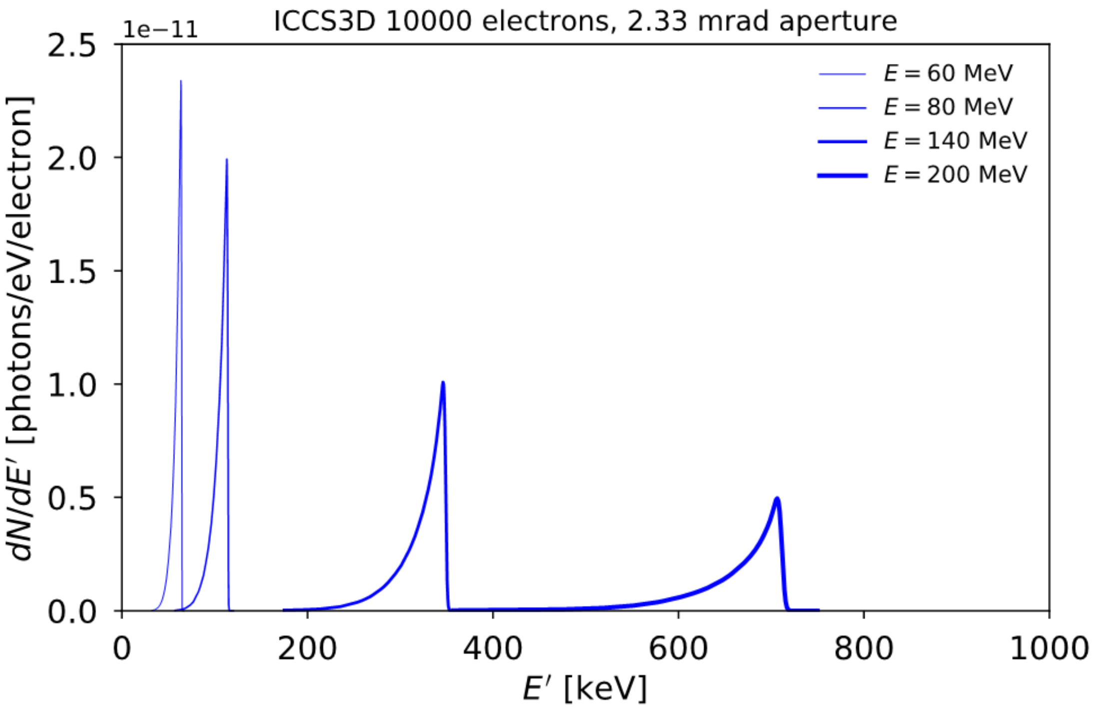
ThomX: Technical design report

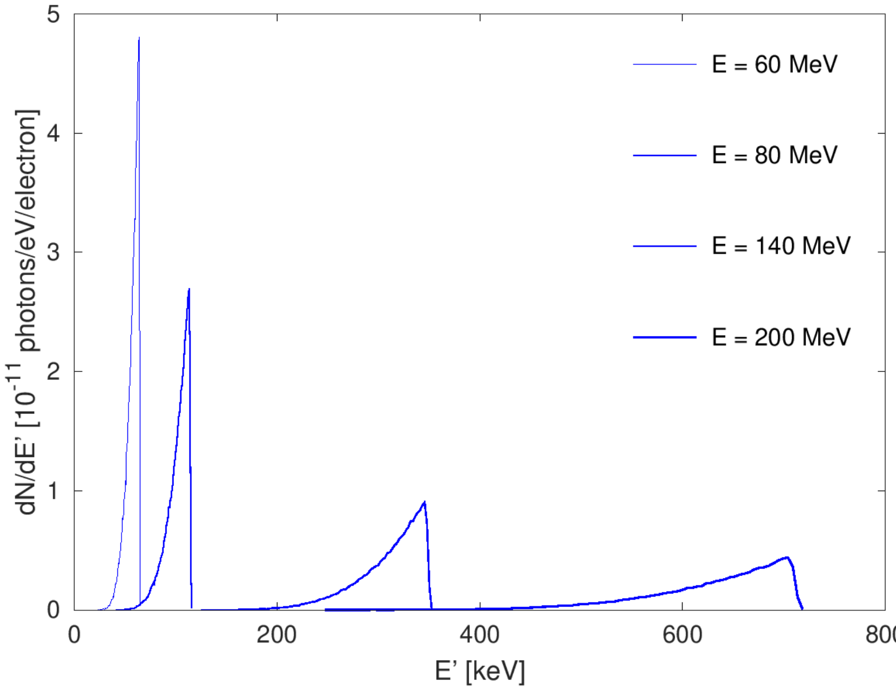
Benchmark of photon spectra

```
<E>          # e-beam: mean energy Ee [eV]
0.002        # e-beam: relative energy spread [unitless]
40.0e-6      # e-beam: horizontal size sigma_e_x [m]
40.0e-6      # e-beam: vertical size sigma_e_y [m]
1e-5         # e-beam: horizontal normalized emittance eps_x [m rad]
1e-5         # e-beam: vertical normalized emittance eps_y [m rad]
```

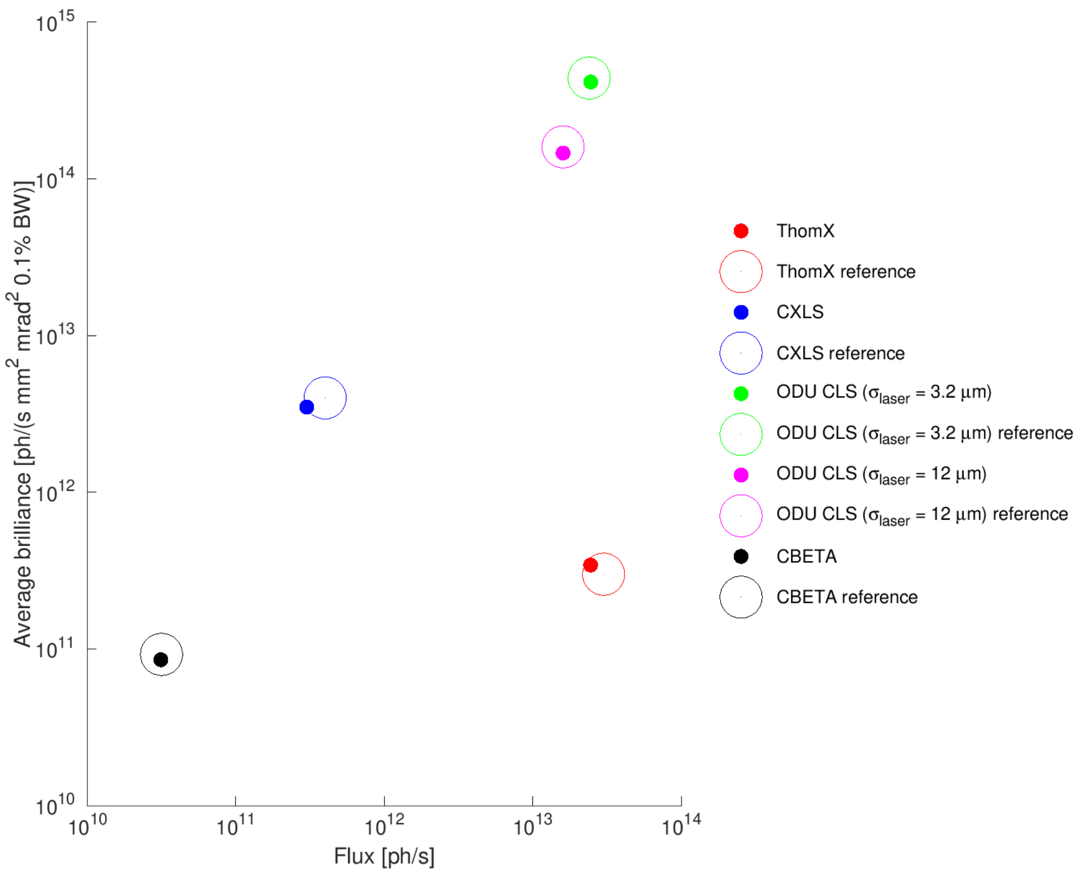
$E = 60, 80, 100, 120, 140, 160, 180, 200$ MeV

- The change in shape of photon spectra depending on electron beam energy was also benchmarked against an ICCS simulation with input laser parameters from MuCLS and an electron beam of their own design.
- Differences due to:
  - Collection angle; Beam size, changed from β^*; Lack of information given on simulation (Rayleigh length)





Simulation vs Referenced estimates



Differences between reference values could be attributed to:

1. Use of different simulation software. CAIN or COMPTON was typically used for ICS simulations at IP. [1]
2. Use of other flux or brilliance formulas.

- 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.

[1] 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.)

IV. Parametric scans

Parametric scans – CompactLight case

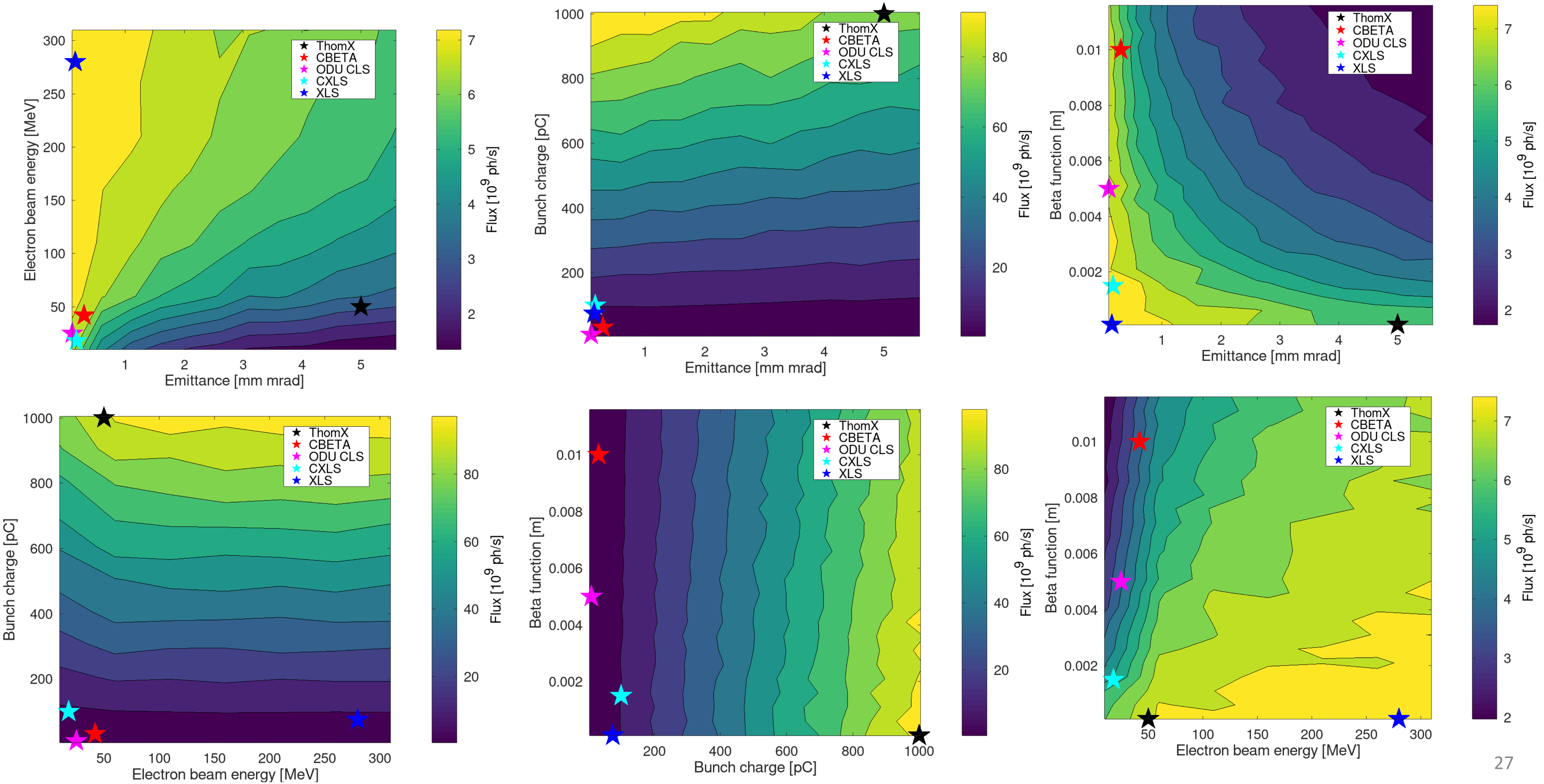
- Scans were done using a linac based on the CompactLight's X-band module and ODU CLS' 1 MW laser.
- Analysing these scans allowed for finding applications that benefited from x-ray parameters: energy, flux and brilliance.
- Parameters were grouped on whether they belonged to the electron or laser beam. All parameters were taken at IP.
- Electron beam parameters: bunch charge, beam energy, beta function and normalised emittance
- Laser beam parameters: spot size, wavelength, pulse length, pulse energy

Parameters of ICS source with one CompactLight linac module and ODU CLS' 1 MW laser

Parameter	Quantity	Units
Beta function (at the IP), β^*	0.1	mm
Crossing angle, ϕ	2	deg
Bunch repetition frequency, f	1	kHz
Nb of bunches per train	2	
Effective repetition frequency, f	2	kHz
Electron kinetic energy, E_{el}	250-300	MeV
Energy spread, $\delta E/E$	5	‰
Bunch length, σ_z	1	ps
Bunch charge, Q_{pc}	75	pC
Normalised emittance, ϵ_x^N, ϵ_y^N	0.15, 0.15	mm mrad
Pulse energy	10	mJ
Pulse length, τ	0.67	ps
Wavelength, λ	1000	nm
Laser spot size, w_0	3.2	μm
Total flux, $\mathcal{F}$	4×10^9	ph/s
Average brilliance, $\mathcal{B}$	2×10^{12}	ph/(s mm2 mrad2 0.1% BW)

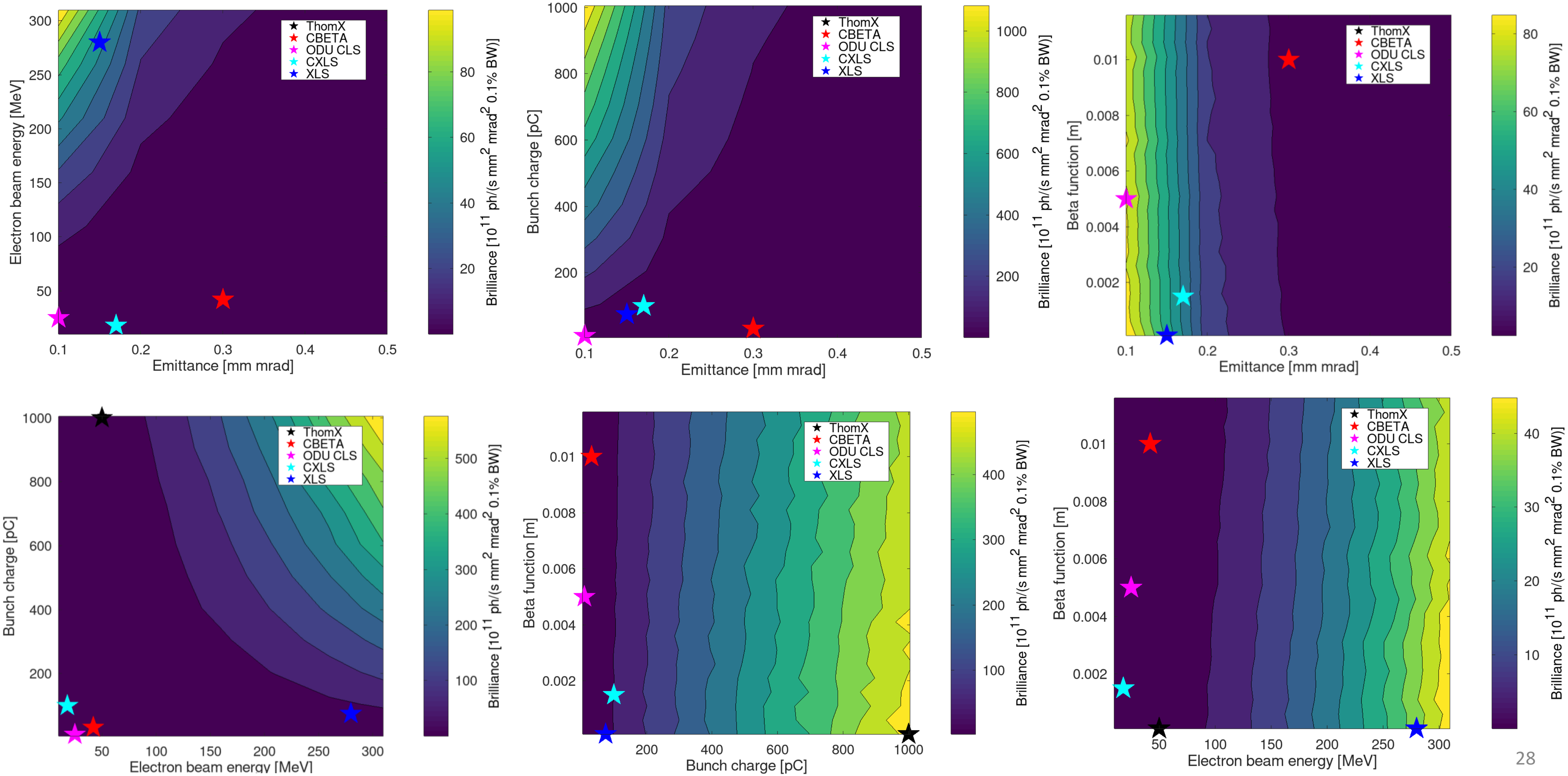
Electron beam parametric scans – Flux (XLS)

Note: flux and brilliance corresponding to ICS sources are not represented in these plots, only the scans' parameters.



Electron beam parametric scans – Brilliance (XLS)

Note: upper scans do not have ThomX's values due to its emittance of 5 mm mrad, which, if included, would have made the plot harder to read.



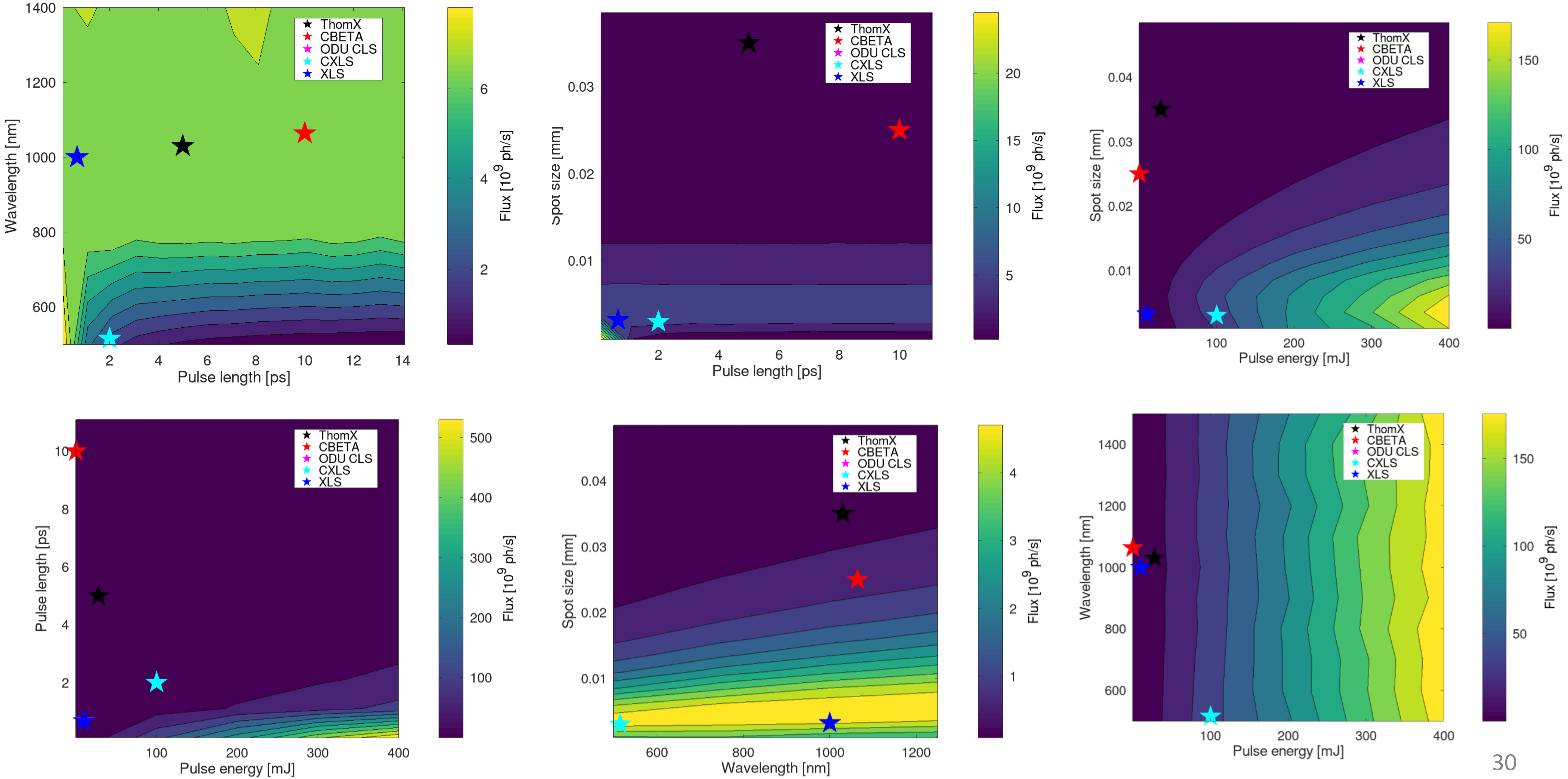
Notes on electron beam scans

- Note the influence emittance had on brilliance scans. Since $\mathcal{B} \sim \epsilon^{-2}$, this was expected.
- To maximise flux/brilliance,

  - increase: bunch charge, beam energy

  - decrease: emittance
- Beta function had no noticeable effect in the order of milimeters. Since maximum flux was reached for $\sigma_e \approx \sigma_l$ and $\sigma_e = \sqrt{\beta^* \epsilon^N / \gamma}$, a small enough beta function ensured the above condition was met.
- Largest changes in flux/brilliance were brought by increasing the bunch charge.

Laser parametric scans – Flux (XLS)



Notes on laser beam scans

- No changes in shape between flux and brilliance plots.
- To maximise flux/brilliance,

  - increase: pulse energy

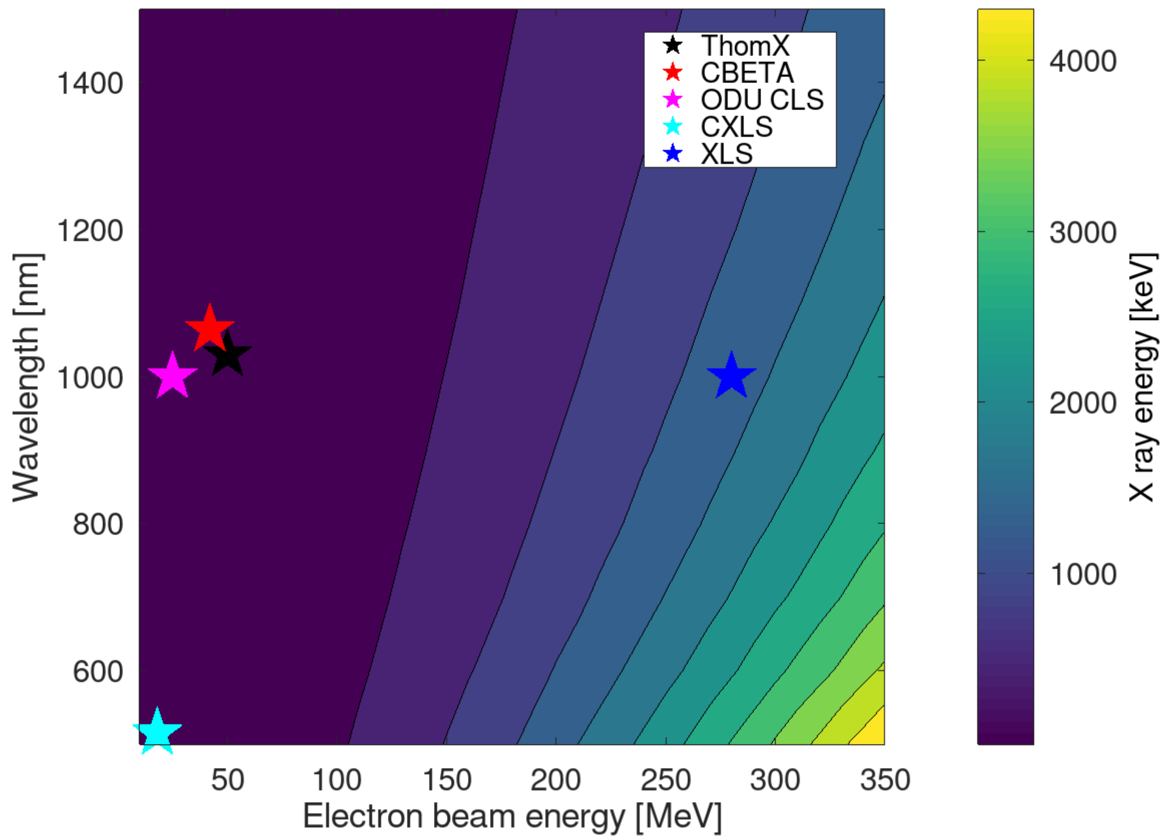
  - decrease: spot size, pulse length
- A change in wavelength did not lead to noticeable shifts in flux/brilliance. It is still important, as it is inversely proportional to the x ray energy.
- Largest changes in flux/brilliance were brought by increasing the pulse energy while decreasing the pulse length.

Parametric scans of x ray energy

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

$$E_X = 2\gamma^2 E_L \frac{1+\cos\theta_c}{1+\gamma^2\theta^2}$$

where E_X is the x ray energy, E_L the laser photon energy, θ_c the crossing angle and θ the scattering angle.



Summary – CompactLight parametric scans

- Identified parameters contributing the most to an increase in flux/brilliance: laser pulse energy and bunch charge.
- Using a linac based on the CompactLight's X-band module and the ODU CLS' 1 MW laser, a total flux in the order of 10^9 ph/s could be reached, along with brilliance in the order of 10^{12} ph/(s mm^2 mrad^2 0.1% BW).
- X ray parameters required for various applications were reproduced in the parametric scans. Namely, K-edge subtraction, phase contrast imaging, and XRF would benefit the most from a CompactLight-like source.

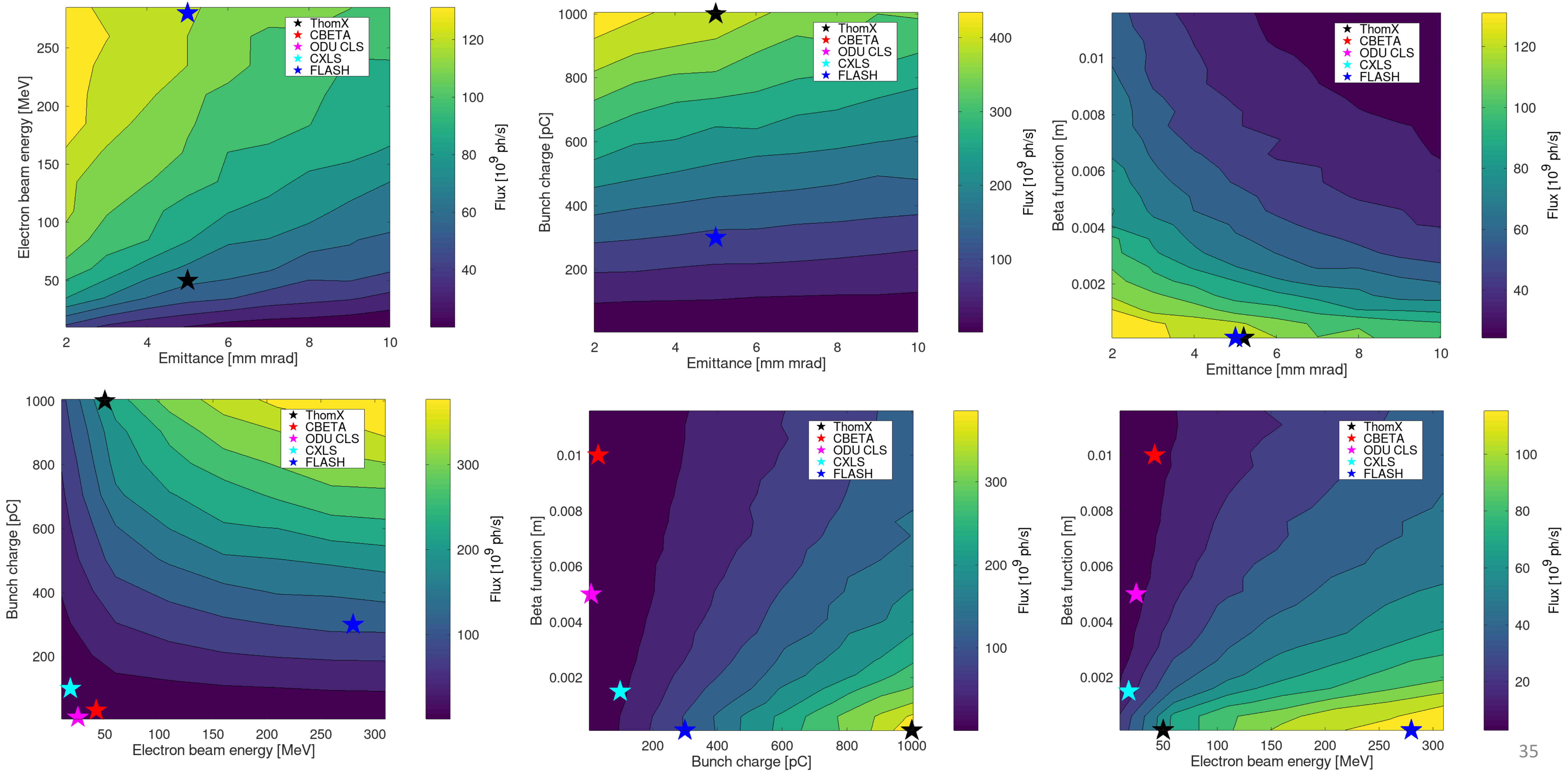
Parametric scans – High-repetition rate injector case

- FLASH-like beam parameters were also considered, again given a 1 MW laser.
- Differences from CompactLight:
  1. $\epsilon^N = 5$ mm mrad.
  2. $f_{rep} = 10$ Hz.
  3. $Nb\ of\ bunches\ per\ train\ =\ 1000$.
  4. Bunch charge = 300 pC
- expect overall an increase in flux due to the high effective repetition frequency, along with decrease in brightness due to larger emittance.

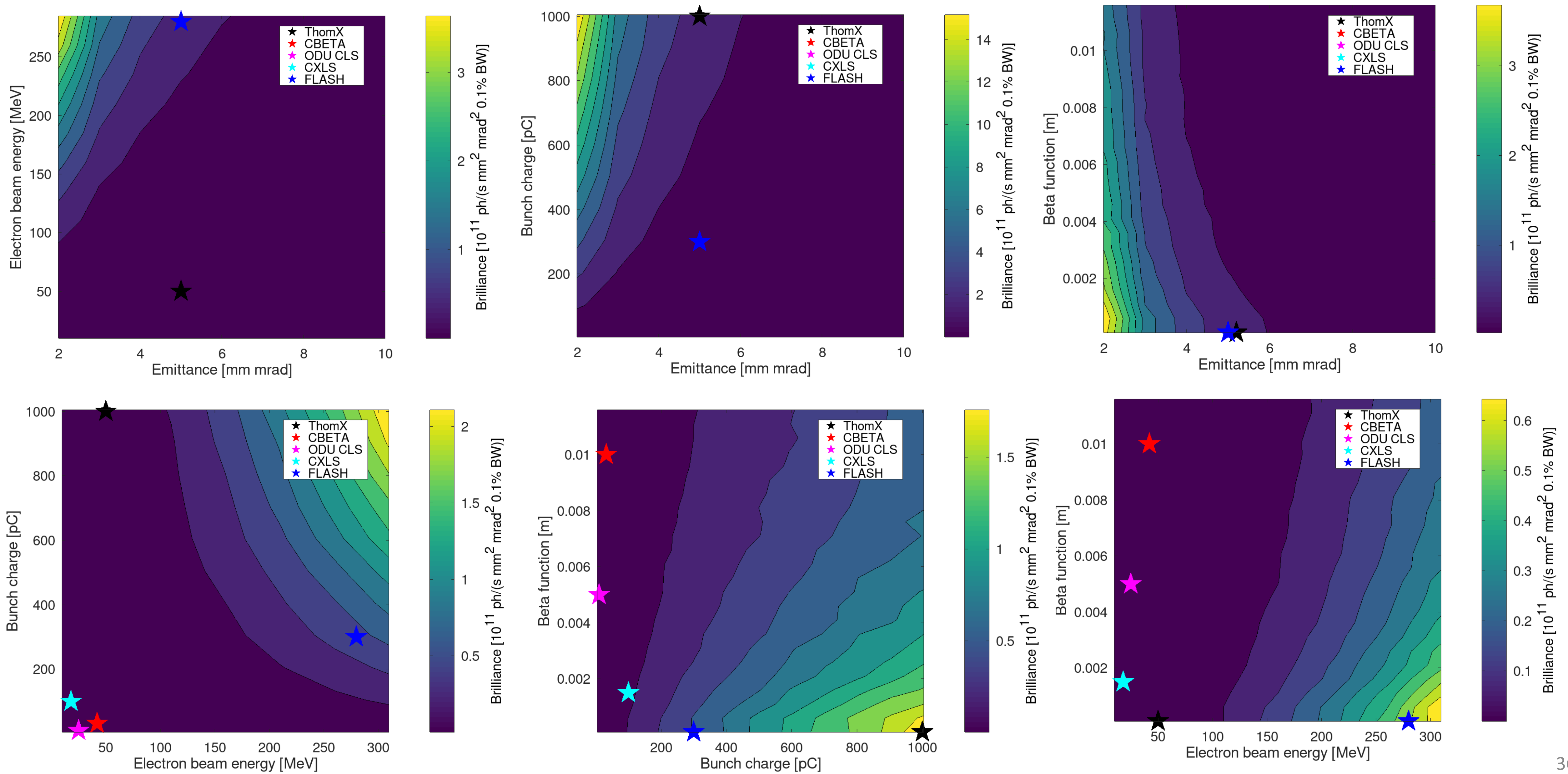
Parameters of FLASH-like linac with ODU CLS' 1 MW laser

Parameter	Quantity	Units
Beta function (at the IP), β^*	0.1	mm
Crossing angle, ϕ	2	deg
Bunch repetition frequency, f	10	Hz
Nb of bunches per train	1000	
Effective repetition frequency, f	10	kHz
Electron kinetic energy, E_{el}	250-300	MeV
Energy spread, $\delta E/E$	5	‰
Bunch length, σ_z	1	ps
Bunch charge, Q_{pc}	300	pC
Normalised emittance, ϵ_x^N, ϵ_y^N	5, 5	mm mrad
Pulse energy	10	mJ
Pulse length, τ	0.67	ps
Wavelength, λ	1000	nm
Laser spot size, w_0	3.2	μm
Total flux, $\mathcal{F}$	10^{11}	ph/s
Average brilliance, $\mathcal{B}$	4×10^{10}	ph/(s mm2 mrad2 0.1% BW)

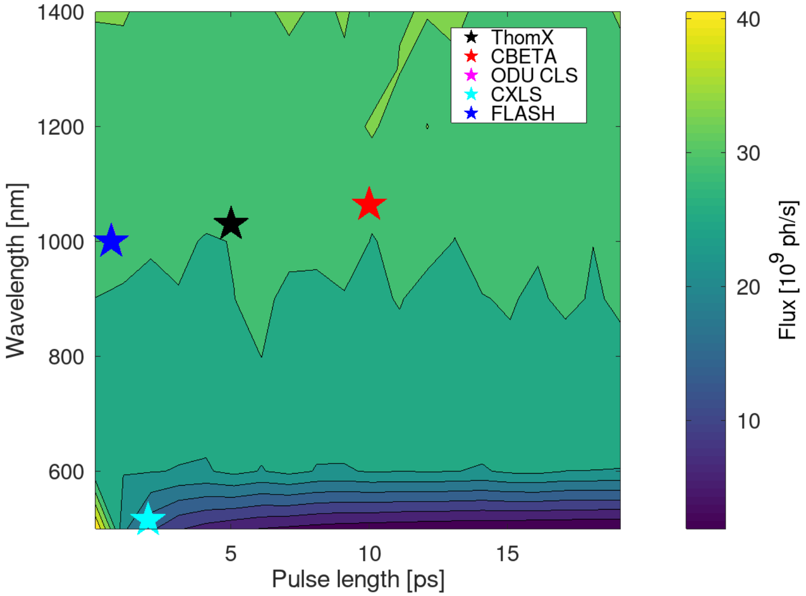
Electron beam parametric scans – Flux (FLASH)

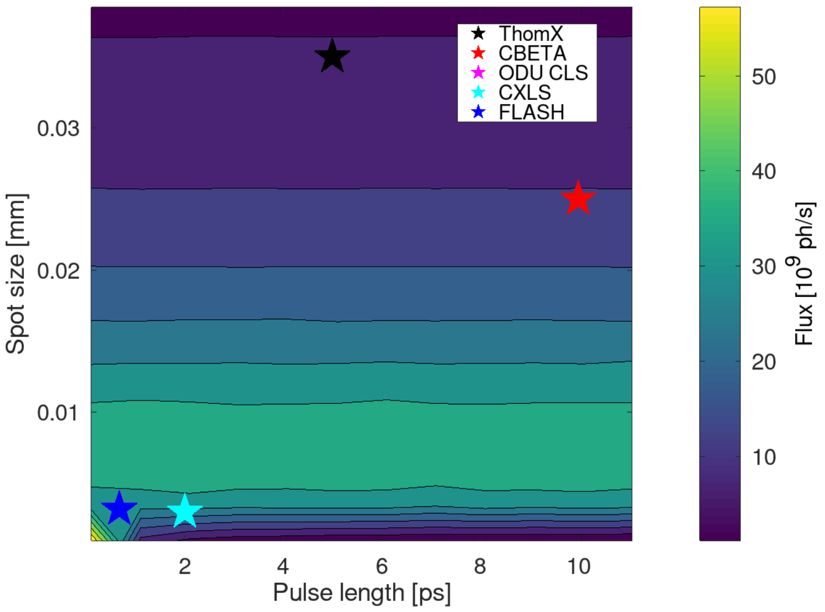


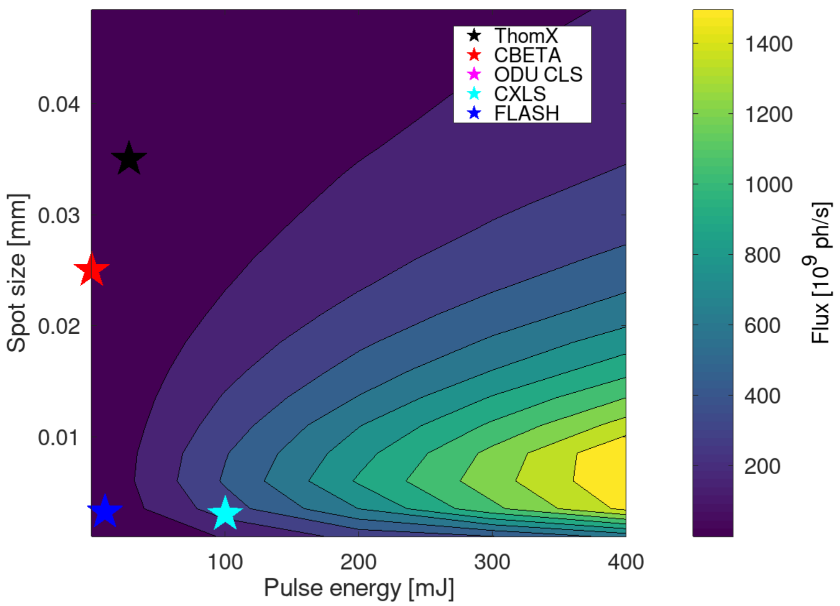
Electron beam parametric scans – Brilliance (FLASH)

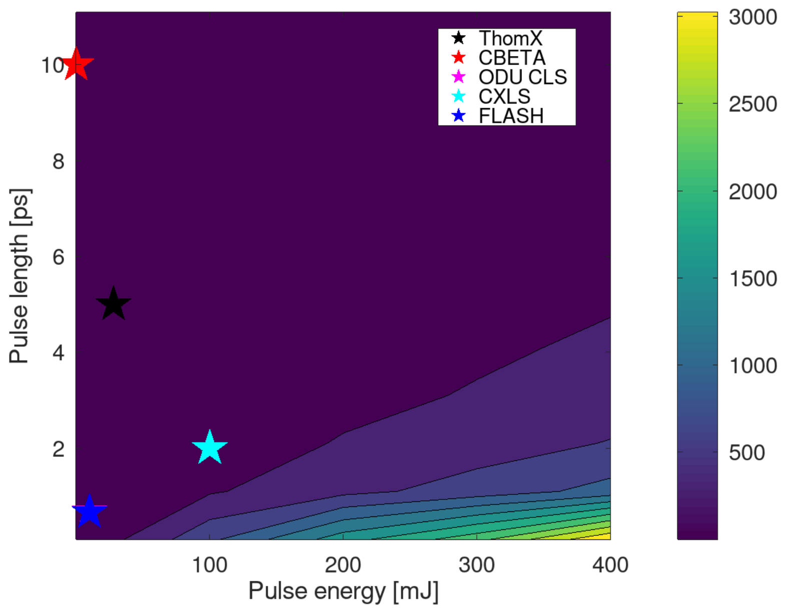


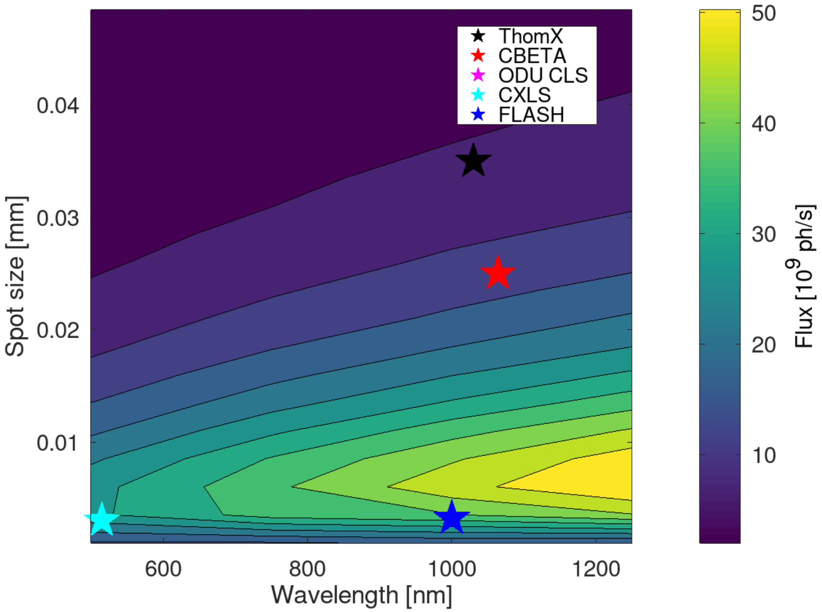
Laser parametric scans – Flux (FLASH)

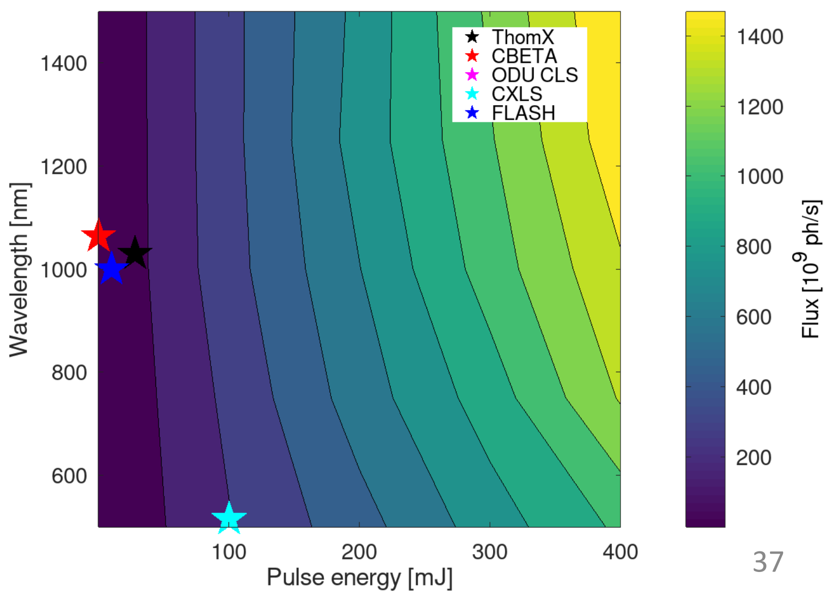








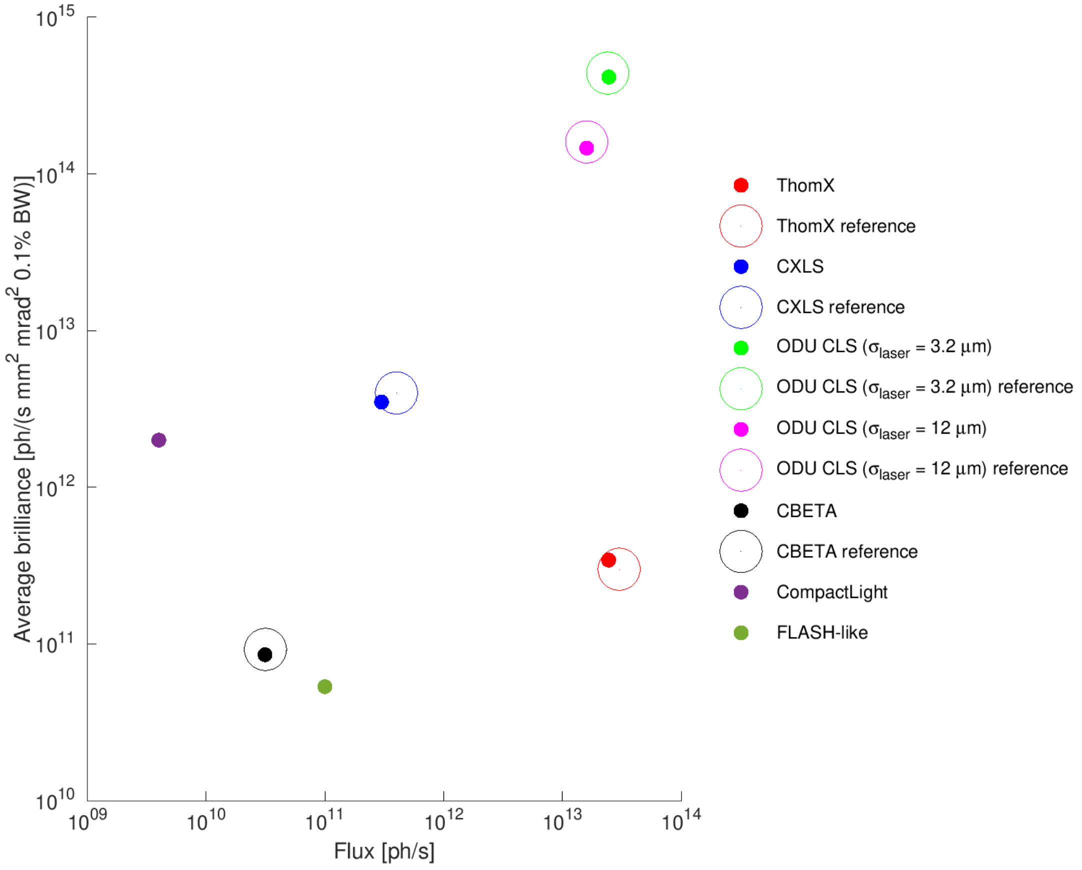




Summary

	CompactLight	FLASH	
Parameter	Quantity		Units
Bunch repetition frequency, f	1	10^{-2}	kHz
Nb of bunches per train	2	1000	
Effective repetition frequency, f	2	10	kHz
Electron kinetic energy, E_{el}	200-300	200-300	MeV
Bunch length, σ_z	1	1	ps
Bunch charge, Q_{pc}	75	300	pC
Normalised emittance, ϵ_x^N, ϵ_y^N	0.15	5	mm mrad
Total flux, $\mathcal{F}$	4×10^9	10^{11}	ph/s
Average brilliance, $\mathcal{B}$	2×10^{12}	4×10^{10}	ph/(s mm2 mrad2 0.1% BW)

Conclusions /I – Estimated performance



- RF-Track was successfully used to simulate ThomX, CXLS, ODU CLS and CBETA ICS sources at the IP.
- Flux and average brilliance were determined with a high precision and accuracy for each set-up.
- RF-Track was then used to simulate a modified ICS sources based on CompactLight and FLASH-like electron beam parameters.

Conclusions /II – Parametric scans

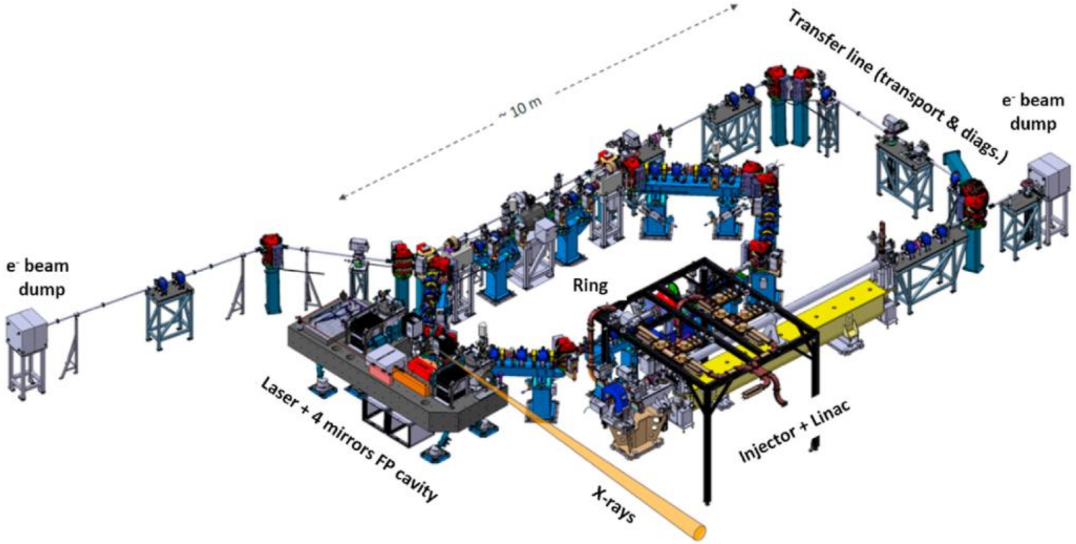
- X ray parameters required for various applications were reproduced in the parametric scans.
- Potential application were identified
  - CompactLight-like sources could be used for:
    1. K-edge subtraction
    2. Phase contrast imaging
    3. X ray fluorescence
  - FLASH-like sources could be used for:
    1. Protein crystallography
    2. Microbeam radiation therapy
    3. Nuclear waste management
- Next steps: document these studies, perform tolerance studies (arrival time mismatch, beam jitter, energy jitter)…

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	Stored average power/MW	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	1	5	28	40	40	16.7	45	90	1E+13	40
MuCLS	45	250					50	1064	0.35	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	1.00E-04	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	24	0.03	10			0.001	60	120		
CBETA	150	32	0.3	0.3			4.3	1000	81	9	0.062	25	25	162.5	33.5	427	1.3E+12	6
ALICE	35	80	10	10			0.6	100	10000000		700			81.25	21.5	21.5		
cERL	20	0.355	0.32	0.28	78	16	2	1064	0.01	10	0.0615	24	32	162.5	6.95	6.95	26000000	
BriXS	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	60		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	0.3	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	1	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		5.00E-04		10			1.00E-05			5.00E+10	

ThomX

- Commissioned storage ring-based ICS source in Orsay [1].
- Has an average brightness larger than any other existing ICS sources, due to a compact electron storage ring and a high finesse optical cavity.
- (add flux andbrilliance of thomx in parameter table)

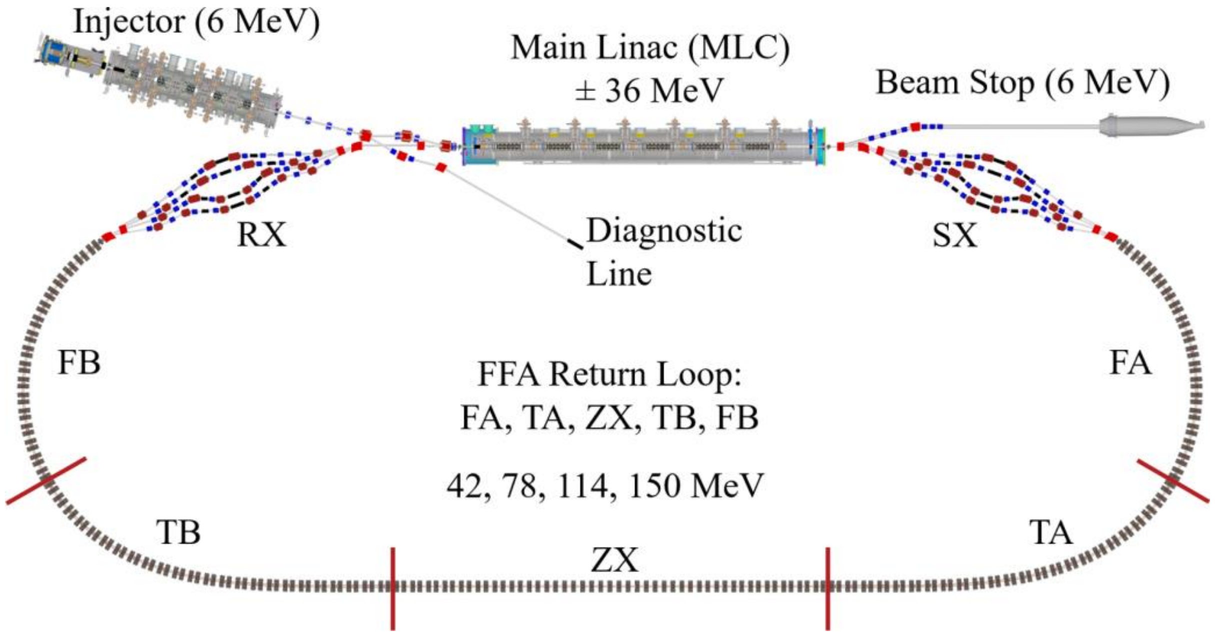


Parameter	Quantity	Units
Beta function (at the IP), β^*	0.1	mm
Crossing angle, ϕ	2	deg
Repetition frequency, f	17.8	MHz
Electron kinetic energy, E_{el}	50 - 70	MeV
Energy spread, $\delta E/E$	3	‰
Bunch length, σ_z	10 - 20	ps
Bunch charge, Q_{pc}	0.05 - 1	nC
Normalised emittance, ϵ_x^N, ϵ_y^N	2 - 9	mm mrad
Pulse energy	28	mJ
Pulse length, τ	5	ps
Wavelength, λ	1030	nm
Laser spot size, w_0	35	μm
Total flux, $\mathcal{F}$	3×10^{13}	ph/s
Average brilliance, $\mathcal{B}$	3×10^{11}	ph/(s mm2 mrad2 0.1% BW)

[1] Kevin Dupraz, et al. (December 01, 2020). The ThomX ICS source. Physics Open, 5, 100051.

CBETA - the Cornell-BNL ERL Test Accelerator

- ERL-based ICS source in development at Cornell University [1].
- Expected to provide scattered photon energies up to 402.5 keV.

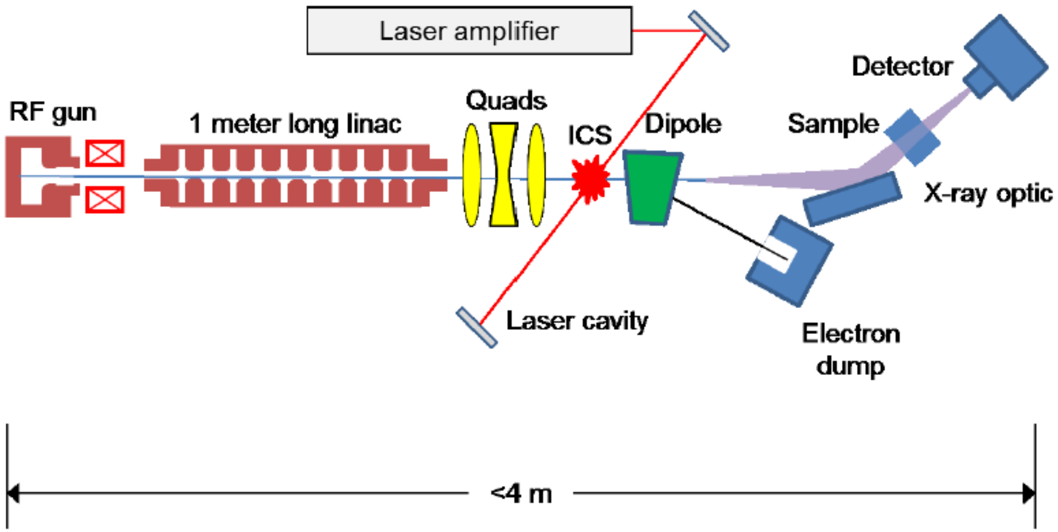


Parameter	Quantity	Units
Beta function (at the IP), β^*	10	mm
Crossing angle, ϕ	5	deg
Repetition frequency, f	162.5	MHz
Electron kinetic energy, E_{el}	42, 78, 114, 150	MeV
Energy spread, $\delta E/E$	0.5	‰
Bunch length, σ_z	3.33	ps
Bunch charge, Q_{pc}	32	pC
Normalised emittance, ϵ_x^N, ϵ_y^N	0.3, 0.3	mm mrad
Pulse energy	0.062	mJ
Pulse length, τ	10	ps
Wavelength, λ	1064	nm
Laser spot size, w_0	25	μm
Total flux, $\mathcal{F}$	3×10^{10}	ph/s
Average brilliance, $\mathcal{B}$	9×10^{10}	ph/(s mm2 mrad2 0.1% BW)

[1] Deitrick, K., et al. (May 01, 2021). Intense monochromatic photons above 100 keV from an inverse Compton source. *Physical Review Accelerators and Beams, 24,* 5.)

CXLS - Compact x-ray Light Source

- Linac-based ICS source designed at MIT and currently being commissioned [1].
- Expected to provide x-ray parameters far beyond existing lab sources, including flux in the order of 10^{14} ph/s.

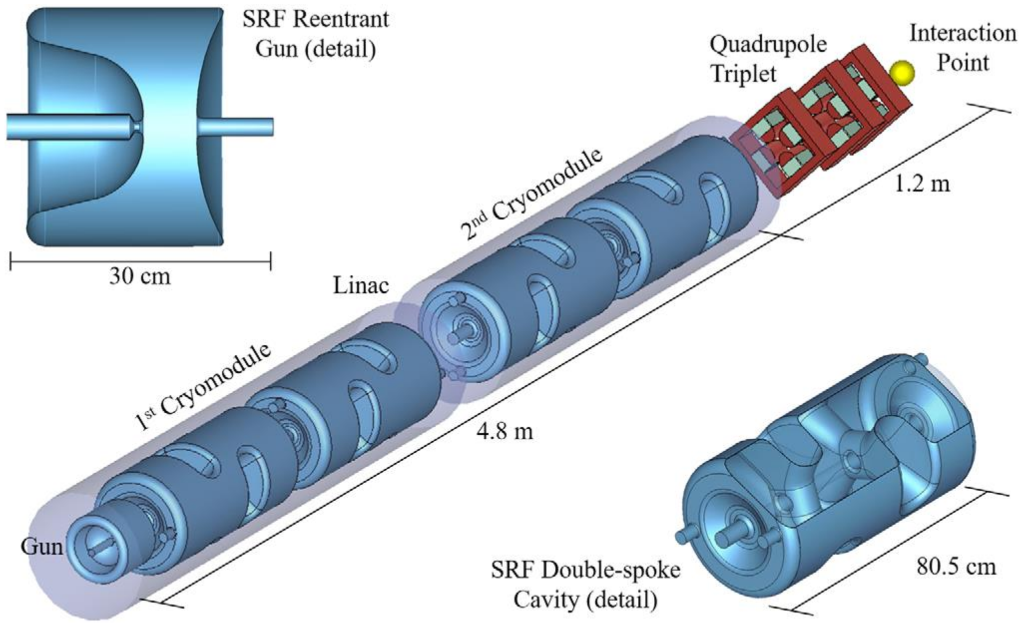


Parameter	Quantity	Units
Beta function (at the IP), β^*	1.5	mm
Crossing angle, ϕ	2.86	deg
Bunch repetition frequency, f	1	kHz
Nb of bunches per train	100	
Effective repetition frequency, f	100	kHz
Bunch spacing	5	ns
Electron kinetic energy, E_{el}	8 - 40	MeV
Energy spread, $\delta E/E$	0.8	‰
Bunch length, σ_z	0.5	ps
Bunch charge, Q_{pc}	100	pC
Normalised emittance, ϵ_x^N, ϵ_y^N	0.17, 0.17	mm mrad
Pulse energy	100	mJ
Pulse length, τ	2	ps
Wavelength, λ	515, 1030	nm
Laser spot size, w_0	3	μm
Total flux, $\mathcal{F}$	5×10^{11}	ph/s
Average brilliance, $\mathcal{B}$	2×10^{12}	ph/(s mm2 mrad2 0.1% BW)

[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);

ODU CLS - The Old Dominion University Compact Light Source

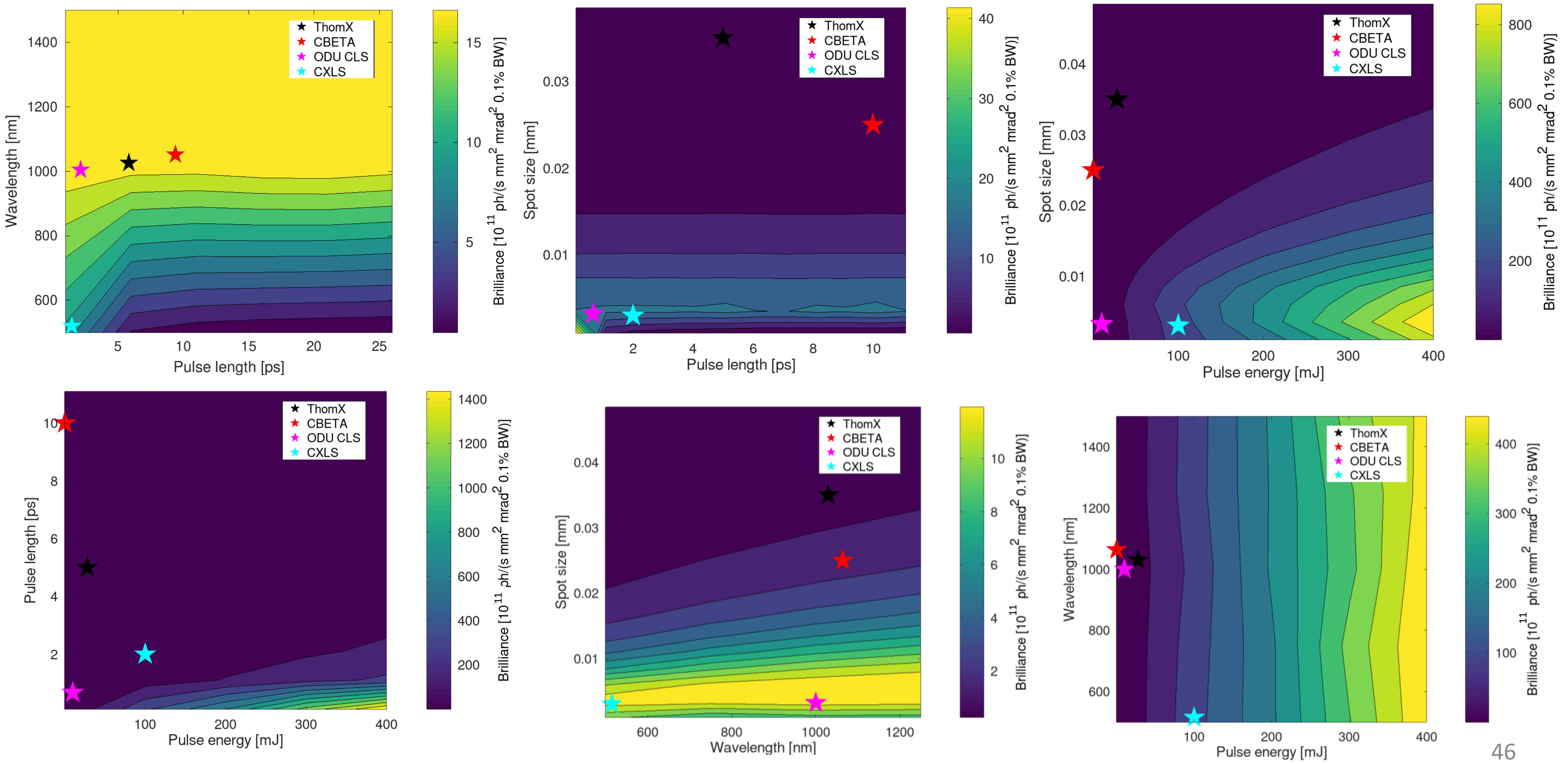
- Linac-based ICS source designed as part of K. E. Deitrick's PhD in 2018 [1].
- Would provide an average brightness larger than any other existing linac-based ICS source by using a 1 MW laser and a superconducting radio frequency (SRF) electron gun.



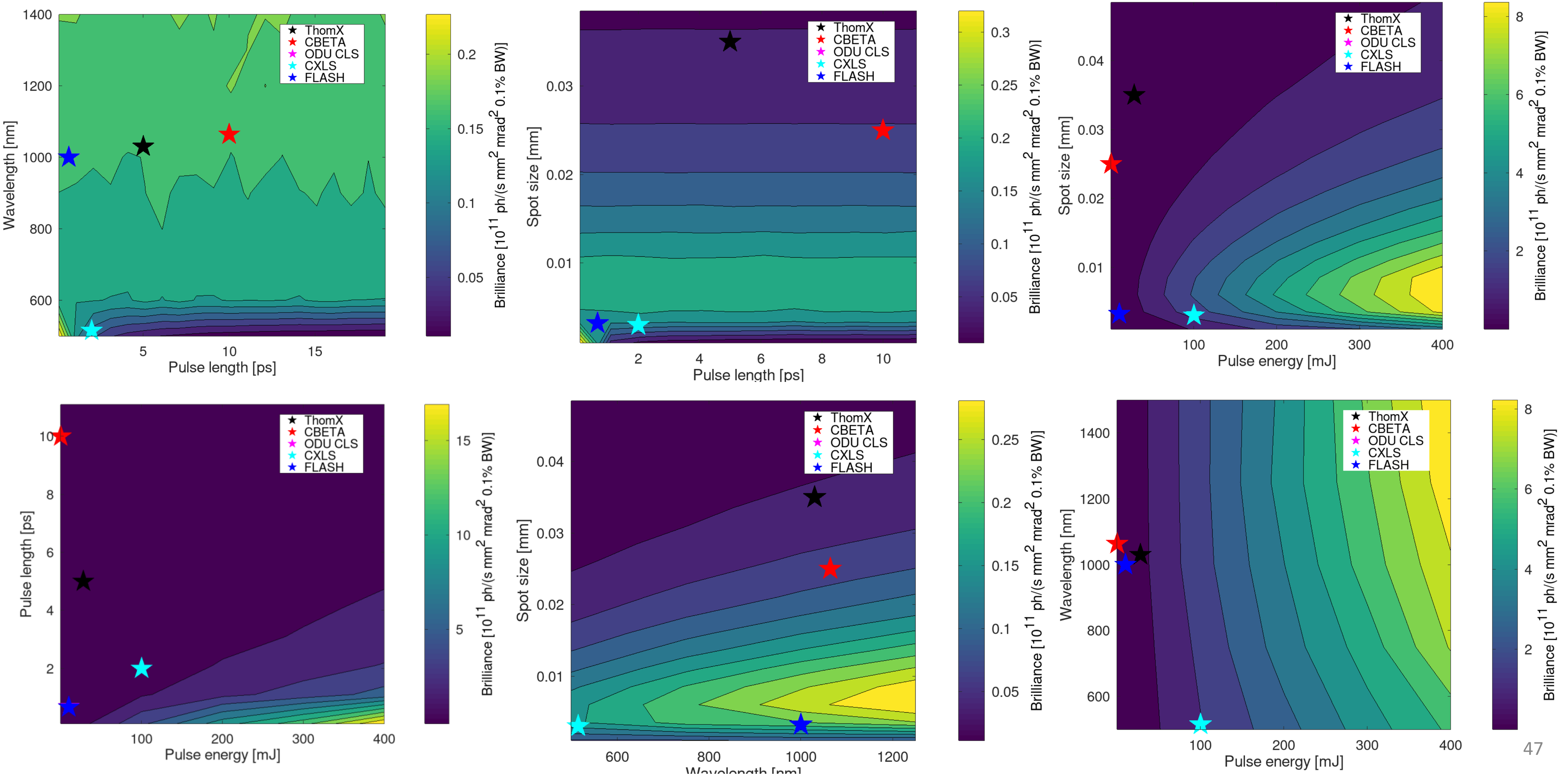
Parameter	Quantity	Units
Beta function (at the IP), β^*	5	mm
Crossing angle, ϕ	2	deg
Repetition frequency, f	100	MHz
Electron kinetic energy, E_{el}	25	MeV
Energy spread, $\delta E/E$	0.45	‰
Bunch length, σ_z	3	psc
Bunch charge, Q_{pc}	10	pC
Normalised emittance, ϵ_x^N, ϵ_y^N	0.1, 0.1	mm mrad
Pulse energy	10	mJ
Pulse length, τ	0.67	ps
Wavelength, λ	1000	nm
Laser spot size, w_0	3.2 / 12	μm
Total flux, $\mathcal{F}$	2×10^{13}	ph/s
Average brilliance, $\mathcal{B}$	4×10^{14}	ph/(s mm2 mrad2 0.1% BW)

[1] 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.)

Laser parametric scans – Brilliance (XLS)



Laser parametric scans – Brilliance (FLASH)



Code sample

- Simulations were done in Octave, using RF-Track.
- Pictured is a code snippet of the CBETA simulations, displaying relevant aspects of the code.

```
%% Define beam-laser IP parameters
L_FP = 0.01; % m, length of the IP region
IP_beta = 0.01; % m, beta star
IP_Lstar = L_FP/2; % m
X_angle = 5; % deg, crossing angle
rep_rate = 162.5e6; % repetition frequency

%% Define beam parameters
Pref = 42; % MeV/c
Pspread = 0.5; % permil, momentum spread
sigma_z = 1; % mm/c
Q_pC = 32; % pC, bunch charge
```

Initialisation of electron beam parameters.

```
%% Define laser-beam IP region
FP = LaserBeam(); % Fabry-Pérot resonator
FP.pulse_energy = 62e-3; % mJ, laser pulse energy
FP.pulse_length = 10; % ps, laser pulse length
FP.wavelength = 1064; % nm, laser wavelength
FP.set_direction(sind(180-X_angle), 0, cosd(180-X_angle)); % depends on crossing angle
FP.length = L_FP;
FP.set_position(IP_Lstar); % m
FP.R = 0.025; % mm, laser beam radius at waist, Gaussian profile
FP.zR = pi * FP.R^2 / (FP.wavelength * 1e-6); % mm Rayleigh length
FP.min_number_of_gammas_per_slice = 5;
FP.set_nsteps(101);
```

Initialisation of laser parameters

To derive the Rayleigh length, the standard formula was used

$$z_R = \frac{\pi w_0^2}{\lambda}$$