ICS studies at CERN

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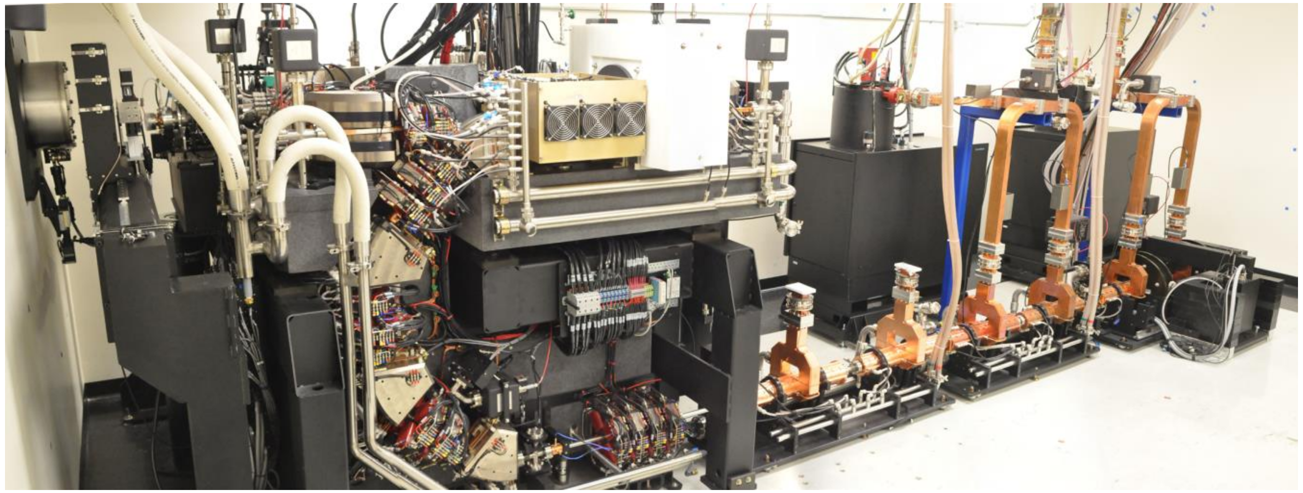
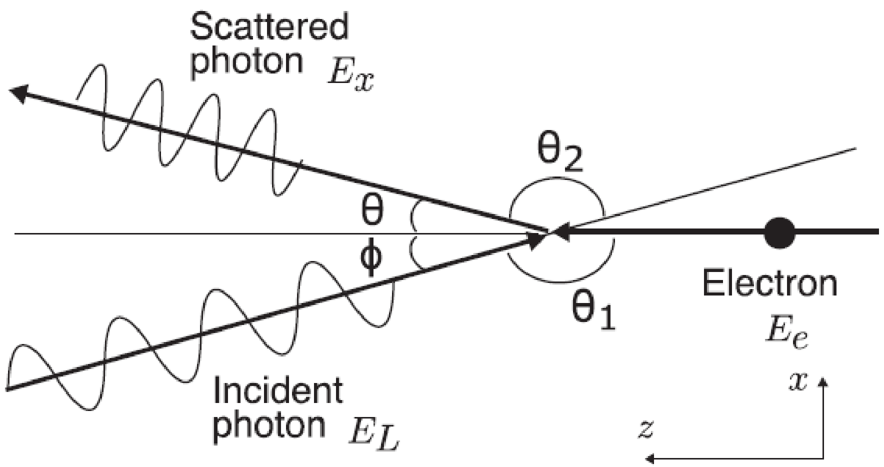
Inverse Compton Scattering (ICS)

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

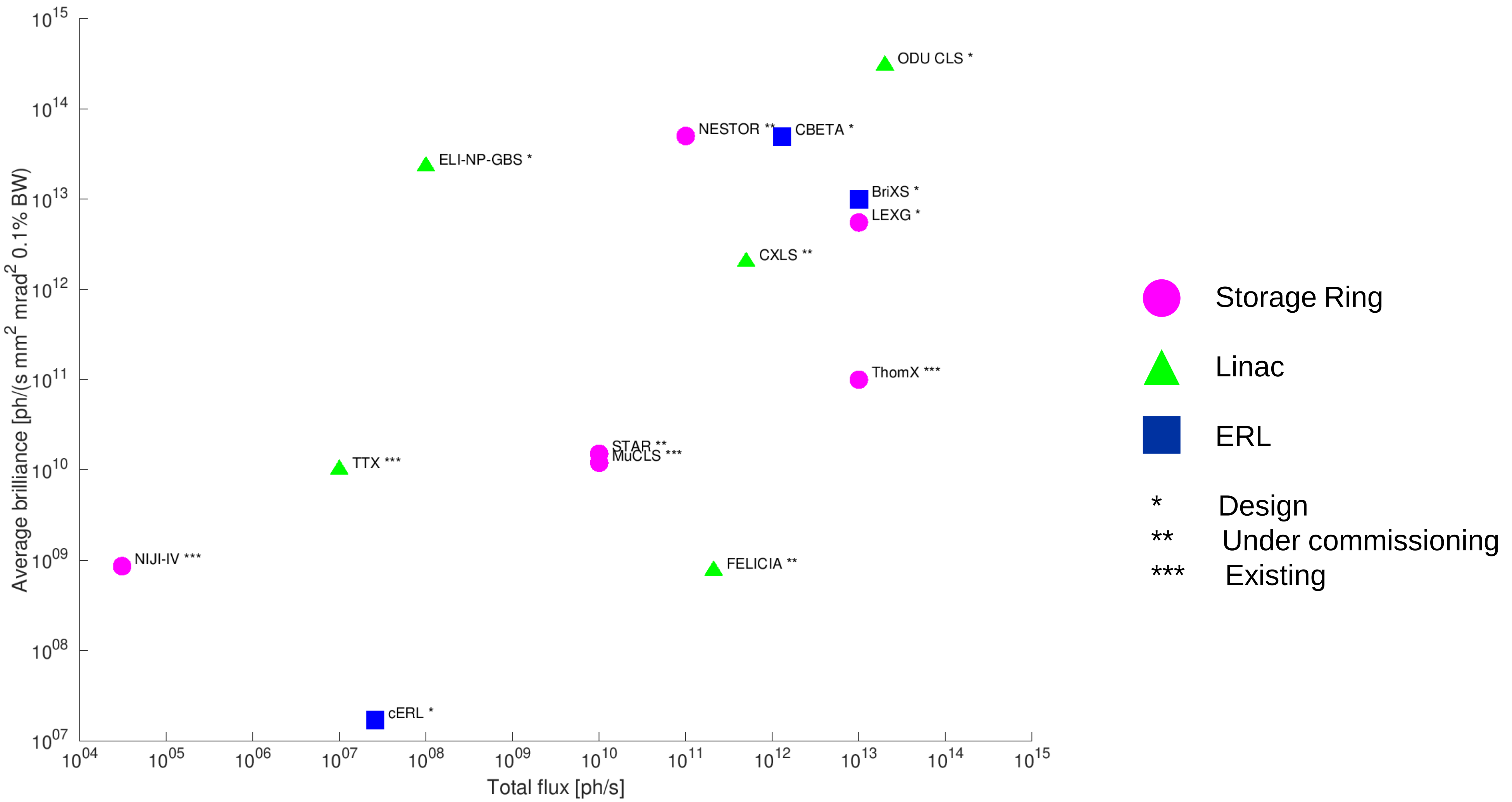
- ICS first described by Feenberg and Primakoff in 1948 [1].
- Several existing ICS sources: ThomX (France), TTX (China), MuCLS (Germany), etc.
- Applications include cancer therapy [2], X-ray imaging [3], cultural heritage [4], protein crystallography [5] and nuclear waste management [6].





[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] McCormick, 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
[6] 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.

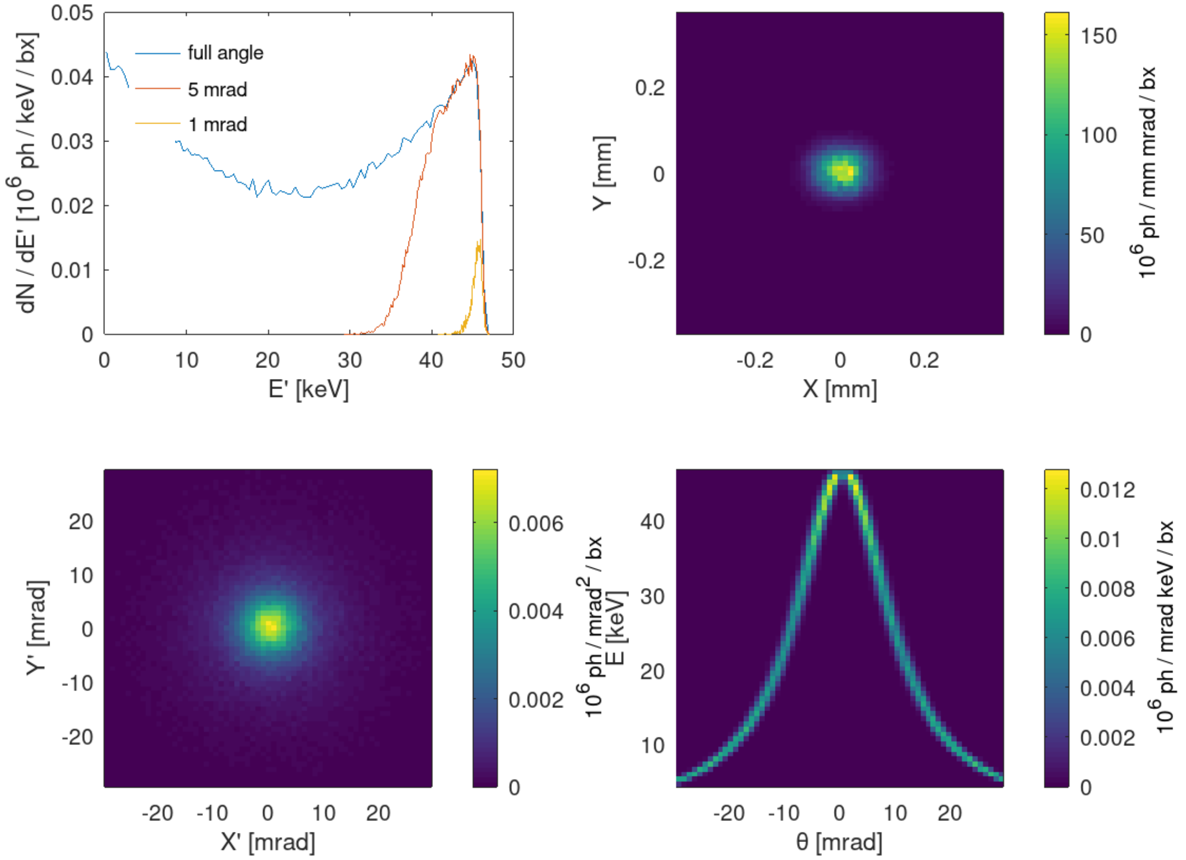
Landscape of ICS sources



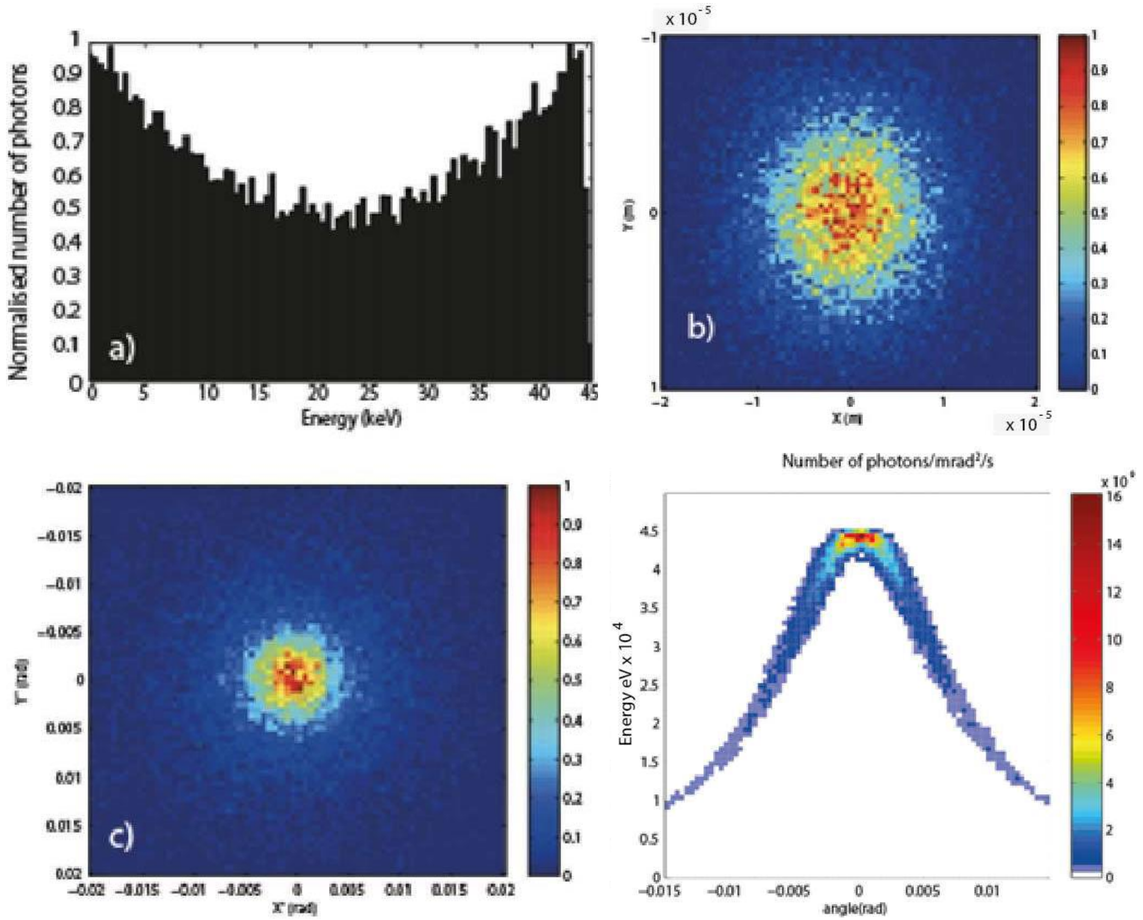
Code benchmark

[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.
- Pictured are RF-Track simulation results for ThomX. [2].

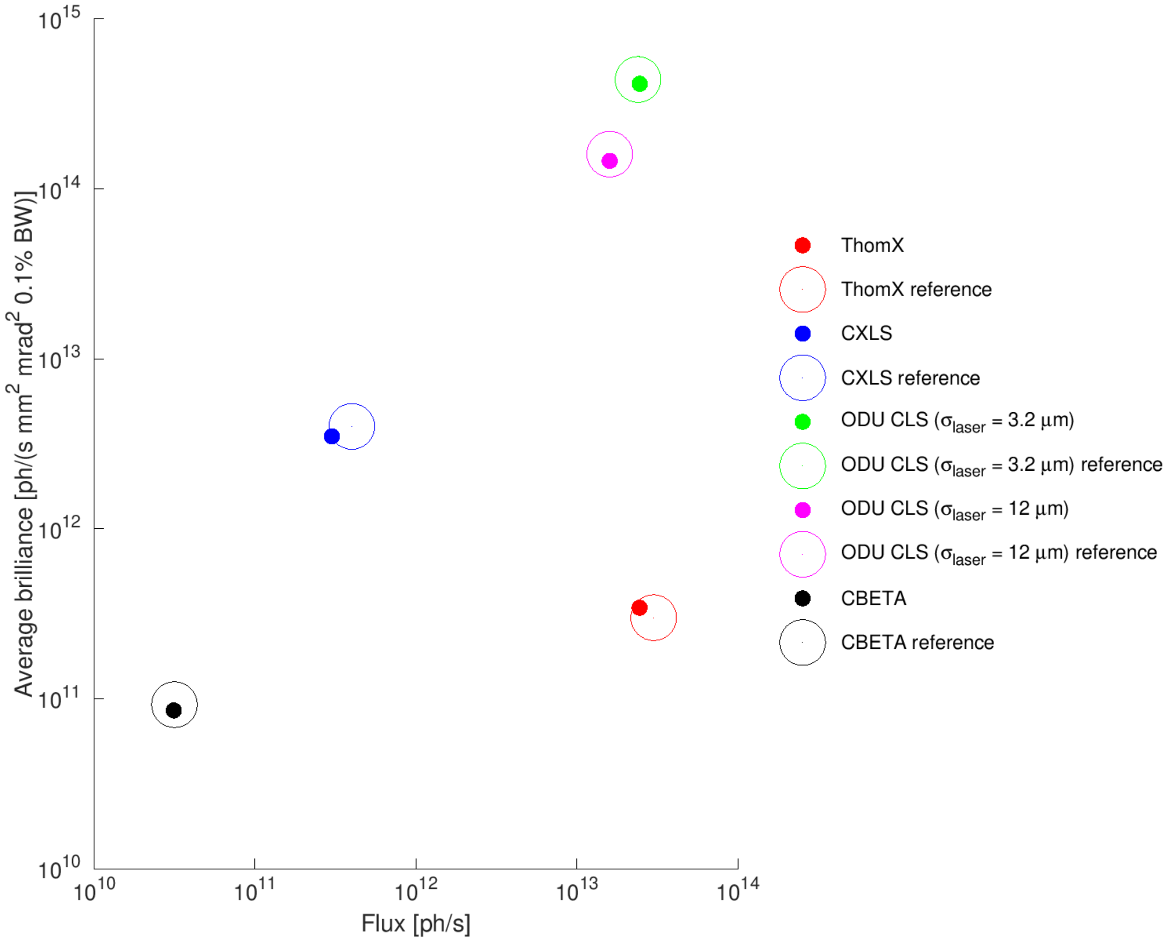


ThomX: RF-Track



ThomX: Technical design report

Benchmark of flux and brilliance calculations



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. [1]

- 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.)

XLS and HPCI electron beam parameters

Parameter	CompactLight (Quantity)	HPCI (Quantity)	Units
Bunch repetition frequency, f	1	10^{-2}	kHz
Nb of bunches per train	50	1000	
Effective repetition frequency, f	50	10	kHz
Bunch length, σ_z	1	1	ps
Bunch charge, Q_{pc}	75-250	300	pC
Bunch spacing	5	2/3	ns
Normalised emittance, ϵ_x^N, ϵ_y^N	0.2-0.4	1-5	mm mrad

- CompactLight (XLS) and high pulse current injector (HPCI) can provide high electron beam energies.
- To maximise flux
  - increase Q_{pC}, number of bunches per train, laser pulse energy E_p

Laser: Preliminary considerations

- A laser similar to TRUMPF's 1 kW Dira 1000 [1] was adopted at the suggestion of Eduardo Granados.

XLS

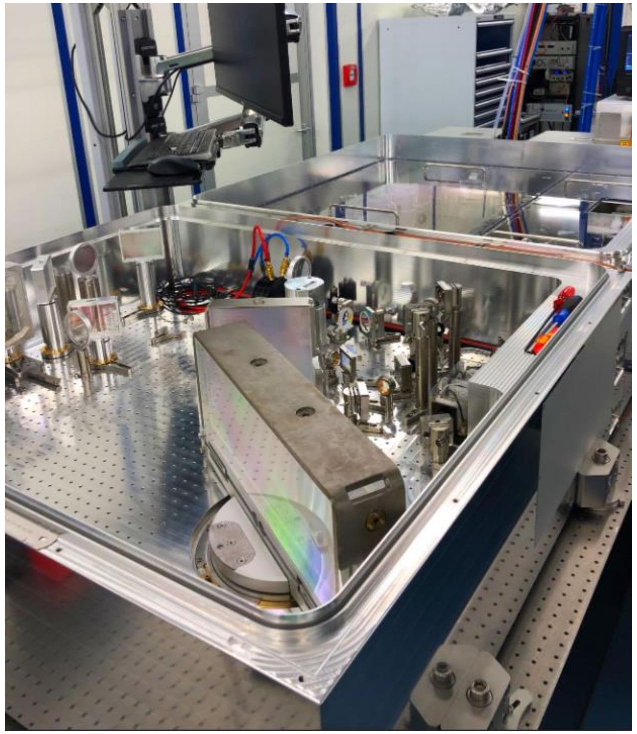
- 50 bunches/pulse and f = 1 kHz -> 1 J/pulse -> E_p = 20 mJ
- Bunch spacing = 5 ns -> 200 MHz enhancement cavity

HPCI

- 1,000 bunches/pulse and f = 10 Hz -> 100 J/pulse -> E_p = 100 mJ
- Bunch spacing = 2/3 ns -> 1.5 GHz enhancement cavity

Enhancement cavities could be used

- In CW for XLS, given the bunch spacing of 5 ns, **E_p = 50 mJ**
- In burst mode for HPCI, given bunch spacing of 2/3 ns, **E_p = 6.6 J**



Parameter	Quantity	Units
Power	1,000	W
Pulse length, τ	0.6	ps
Wavelength, λ	1000	nm
Laser spot size, w_0	12	μm

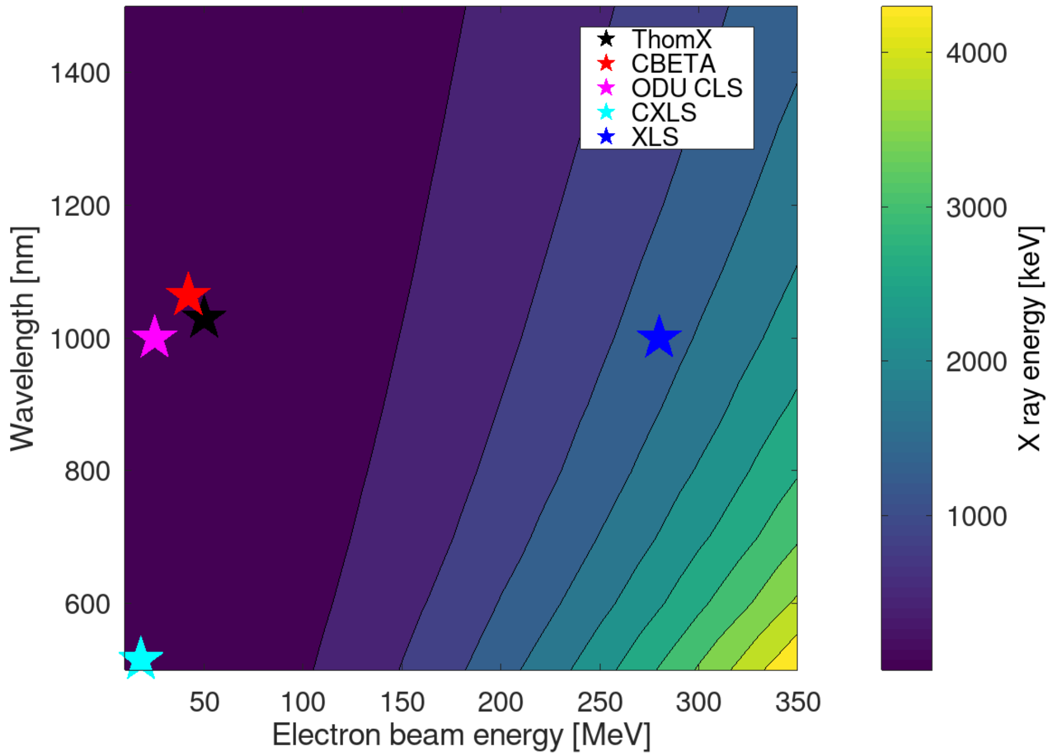
[1] T. Metzger (November 6 2019), Ultrafast Thin-Disk Amplifiers, Talk S55.

Parametric scans of X ray energy

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

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

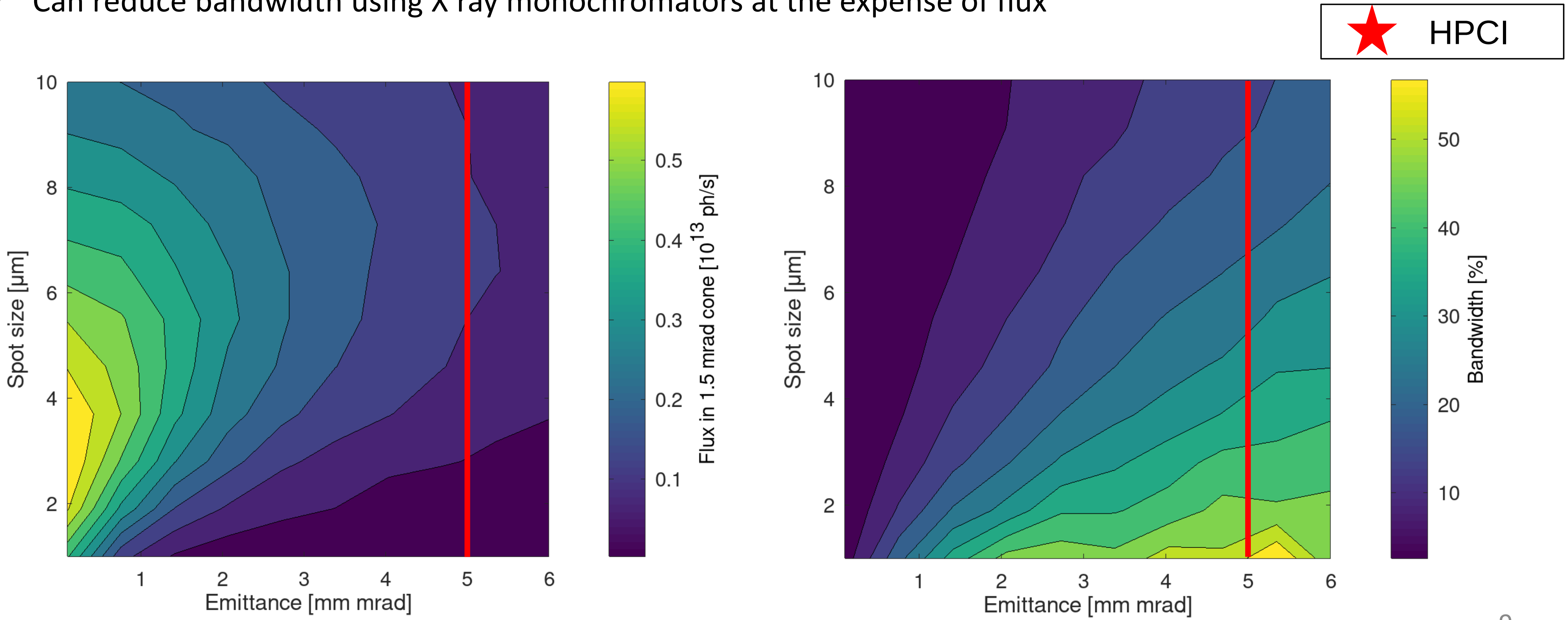
where E_X is the X ray energy, E_L the laser photon energy, θ_c the crossing angle and θ the scattering angle.



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

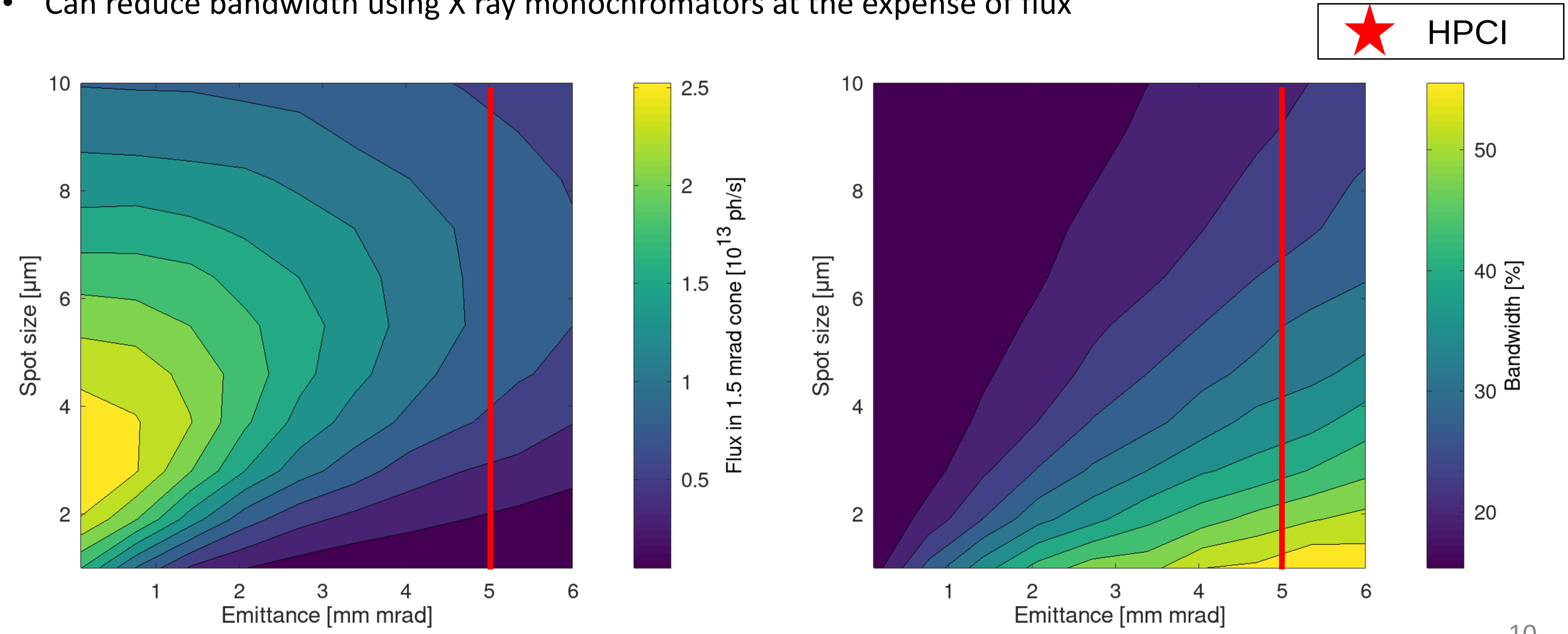
Parametric scans (HPCI) at 100 MeV

- Dira 1000 laser was used, along with HPCI electron gun
- Assumed laser spot size is equal to electron beam size
- Applications typically use flux in a 1-2 mrad cone
- Can reduce bandwidth using X ray monochromators at the expense of flux



Parametric scans (HPCI) at 300 MeV

- Dira 1000 laser was used, along with HPCI electron gun
- Assumed laser spot size is equal to electron beam size
- Applications typically use flux in a 1-2 mrad cone
- Can reduce bandwidth using X ray monochromators at the expense of flux



Parametric scans (HPCI) - Spot sizes at 100 MeV

- Dira 1000 laser was used, along with HPCI electron gun
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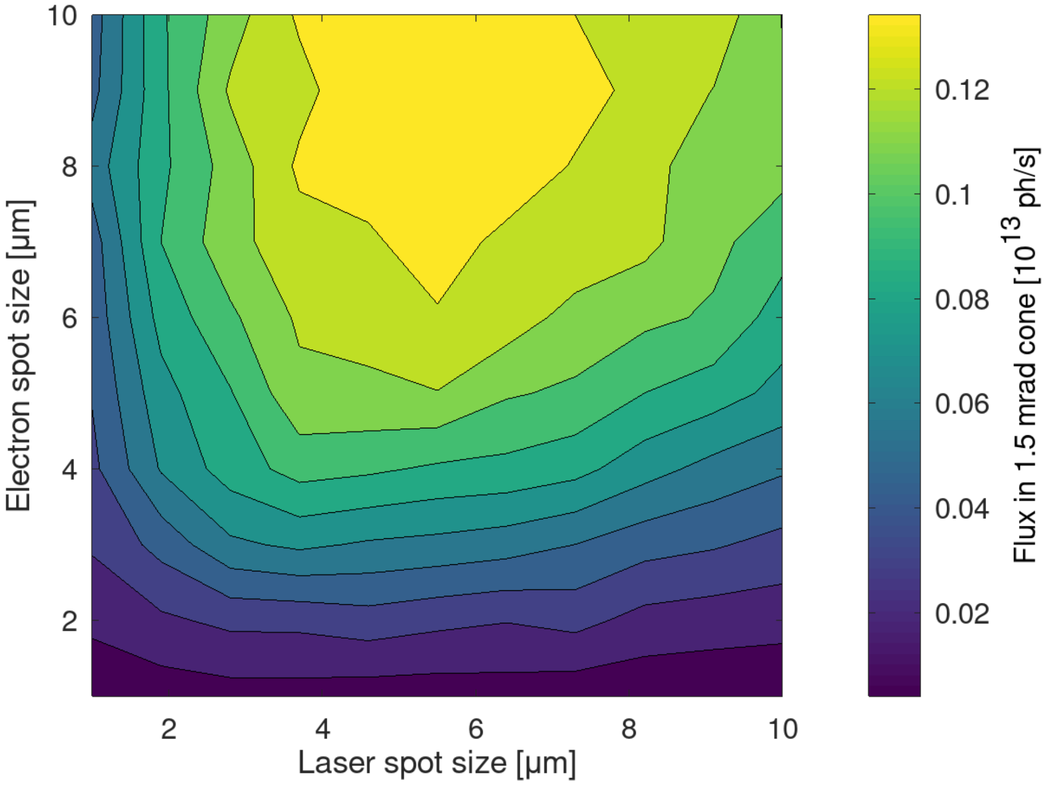

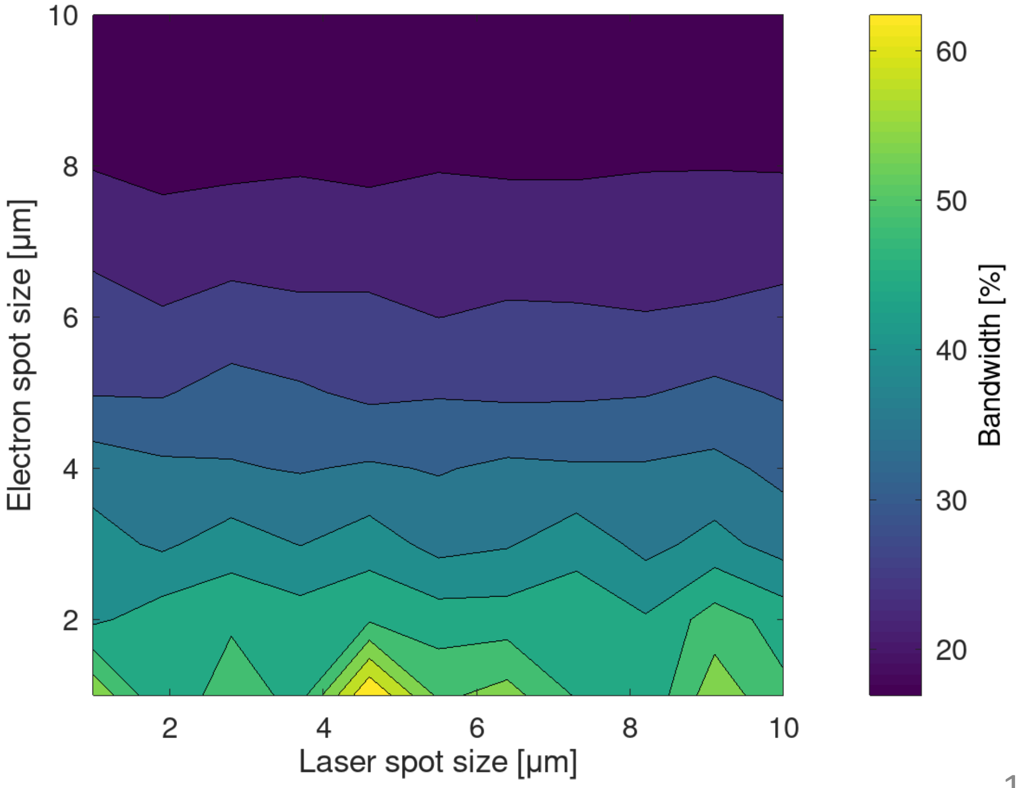

Parametric scans (HPCI) - Spot sizes at 300 MeV

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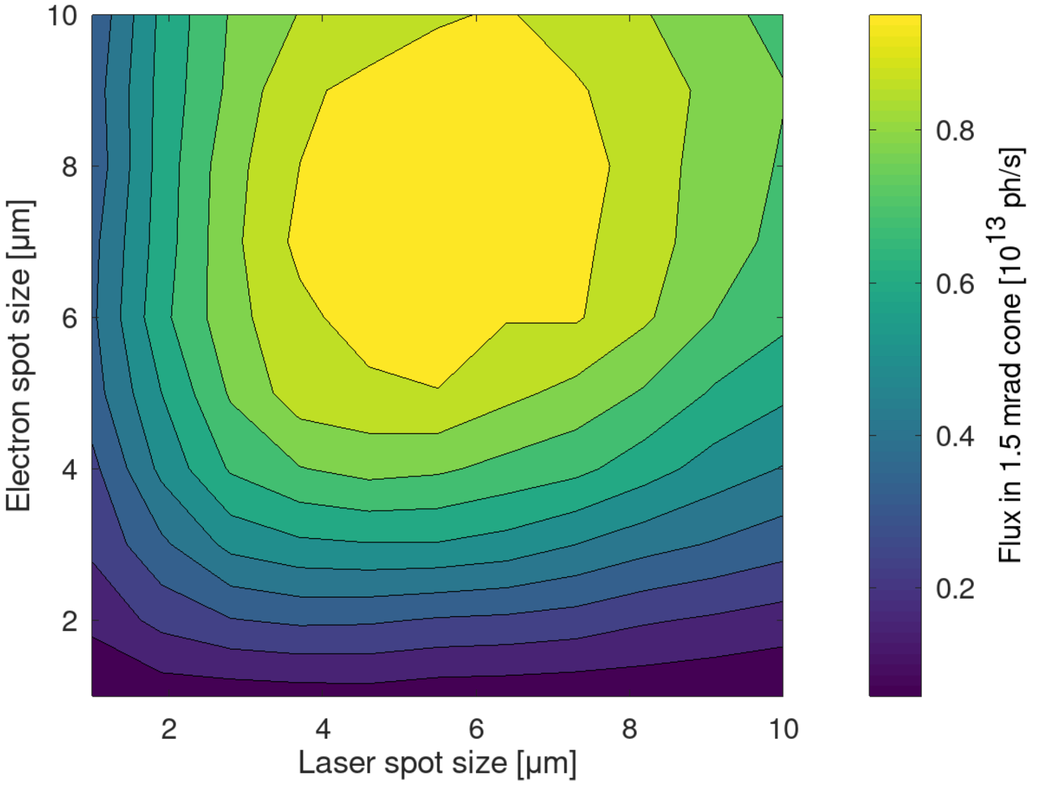
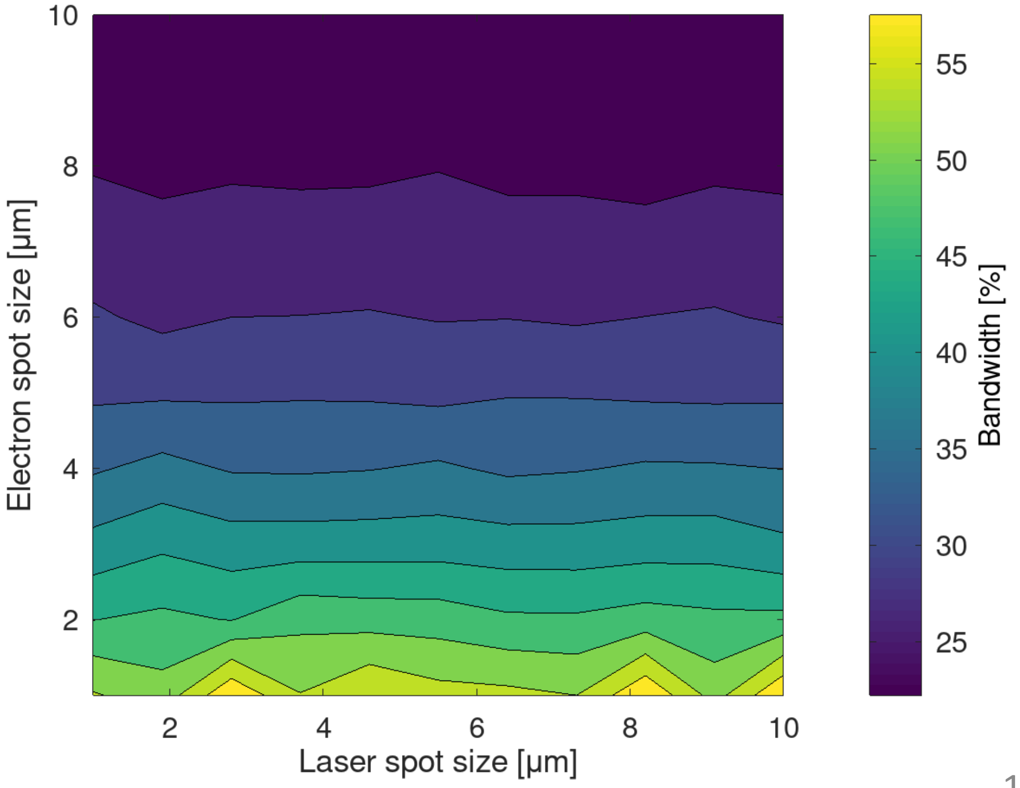
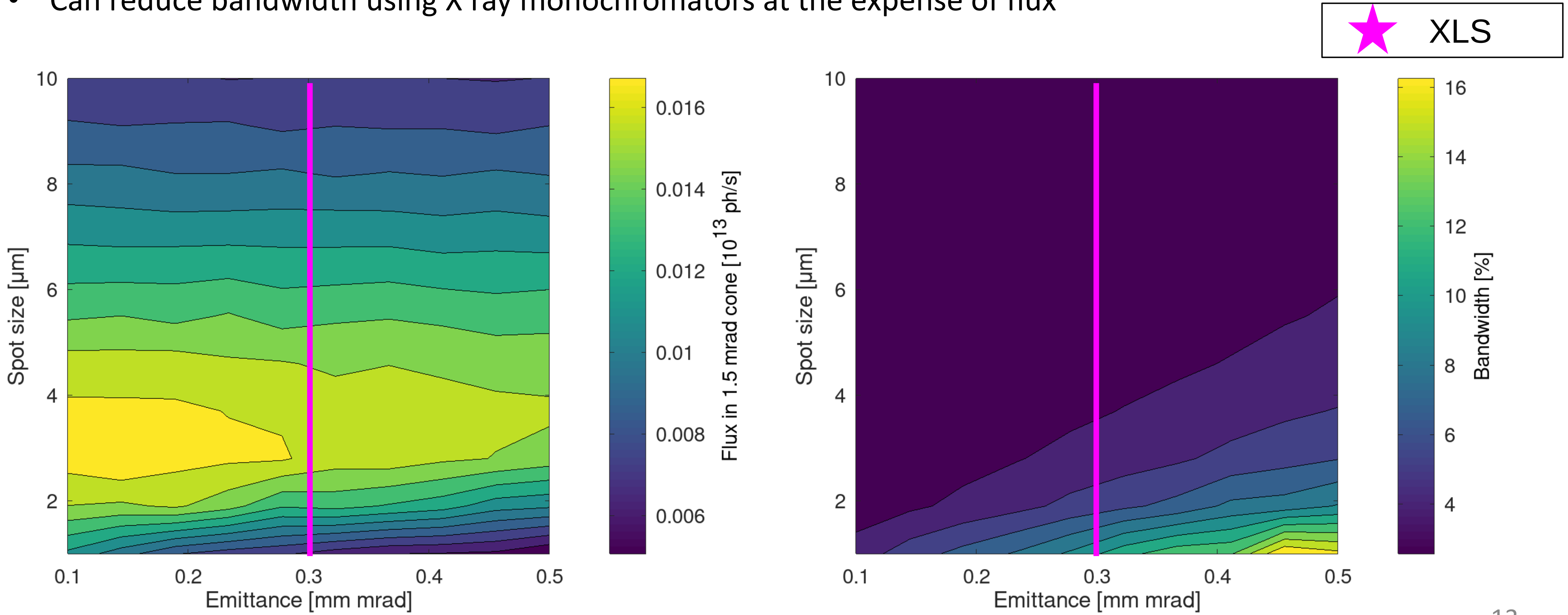




Parametric scans (XLS) at 100 MeV

- Dira 1000 laser was used, along with CompactLight electron gun
- Assumed laser spot size is equal to electron beam size
- Applications typically use flux in a 1-2 mrad cone
- Can reduce bandwidth using X ray monochromators at the expense of flux



Parametric scans (XLS) at 300 MeV

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- Assumed laser spot size is equal to electron beam size
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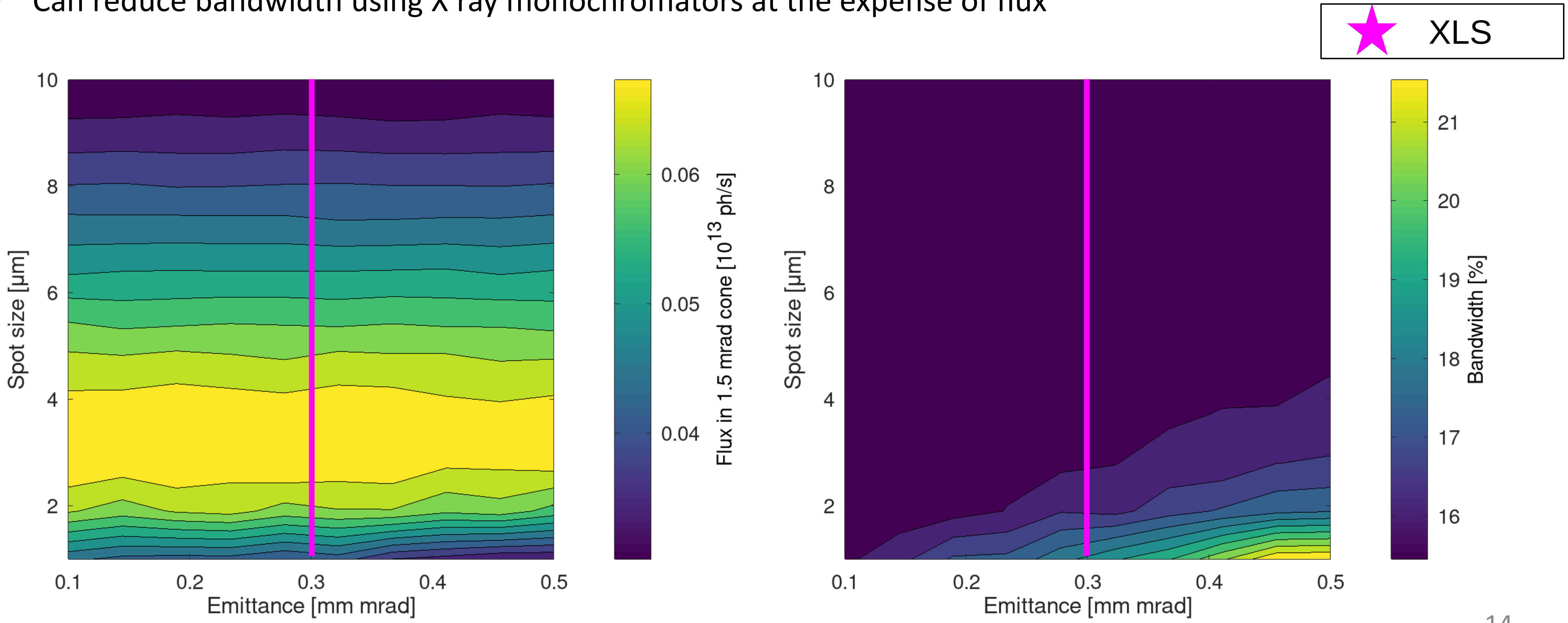
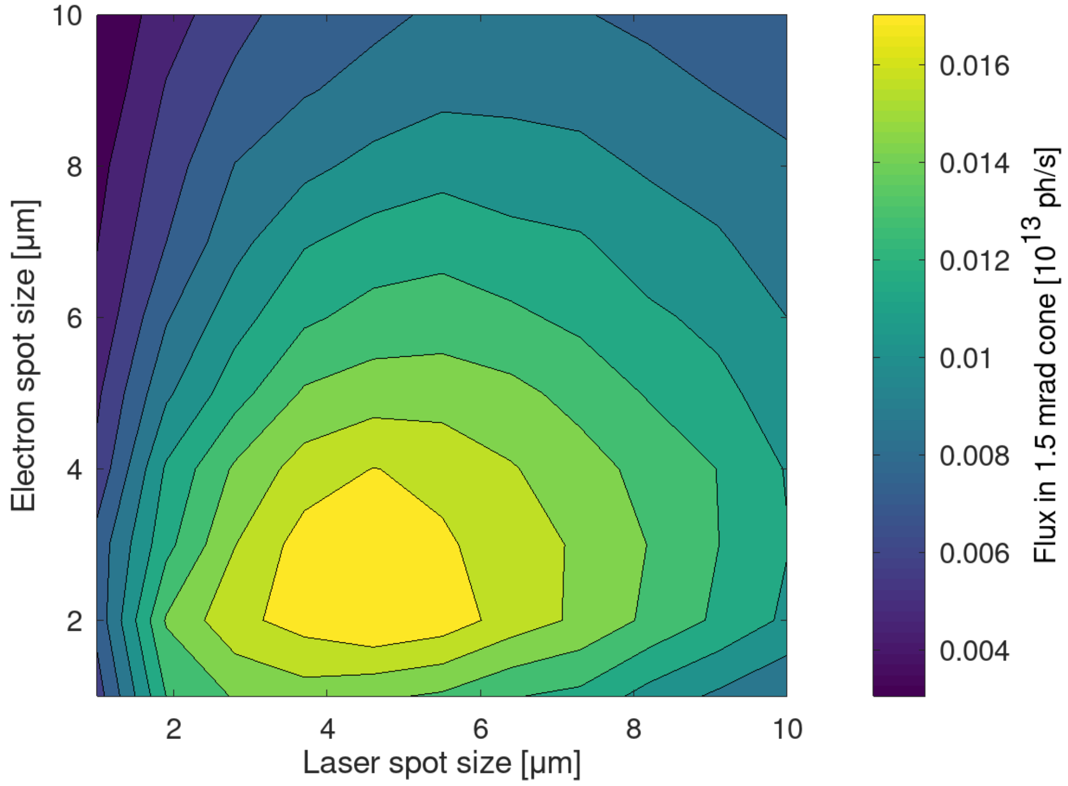
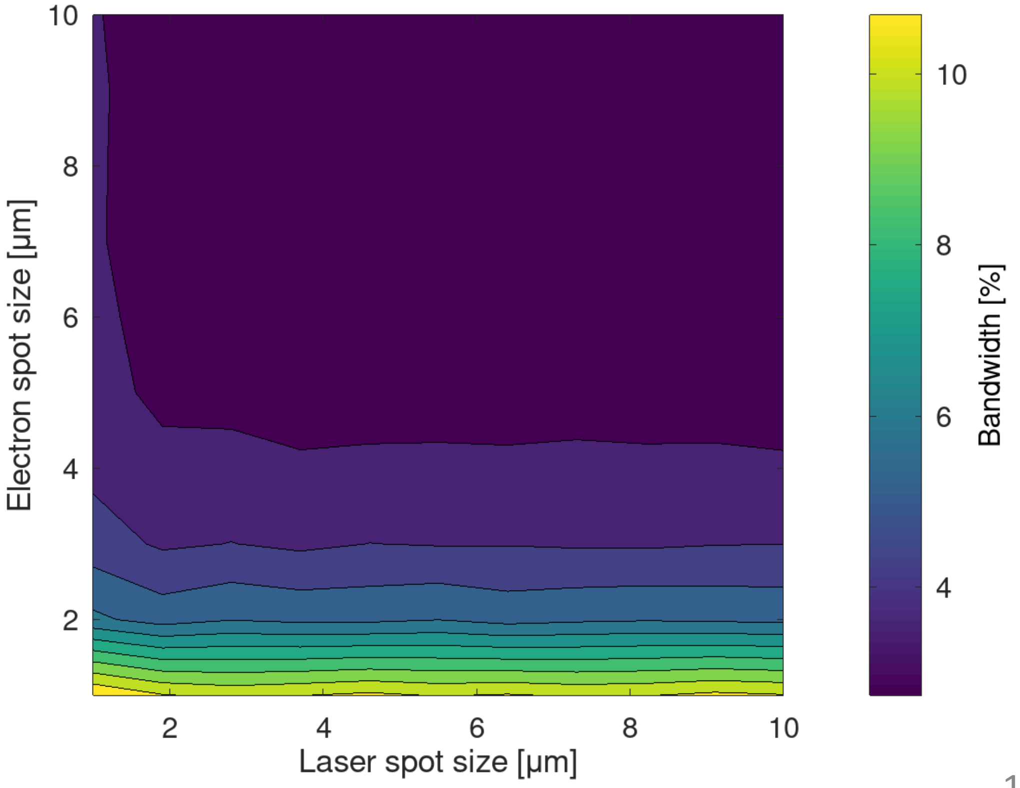


Parametric scans (XLS) - Spot sizes at 100 MeV

- Dira 1000 laser was used, along with 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





Parametric scans (XLS) - Spot sizes at 300 MeV

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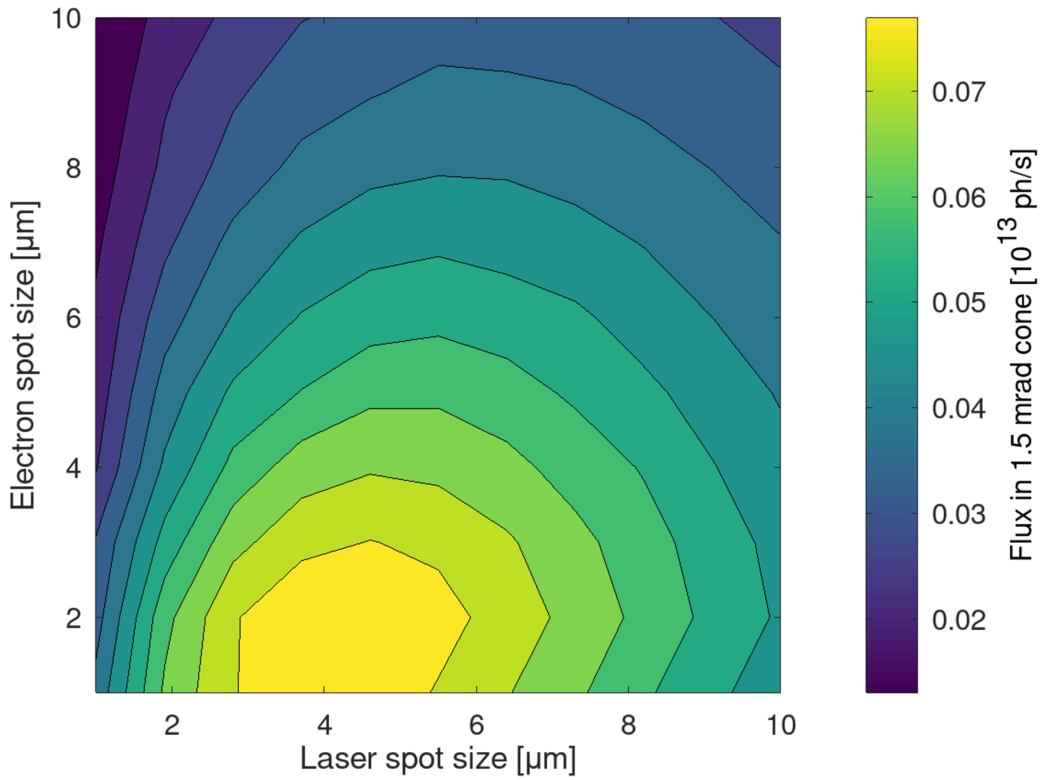
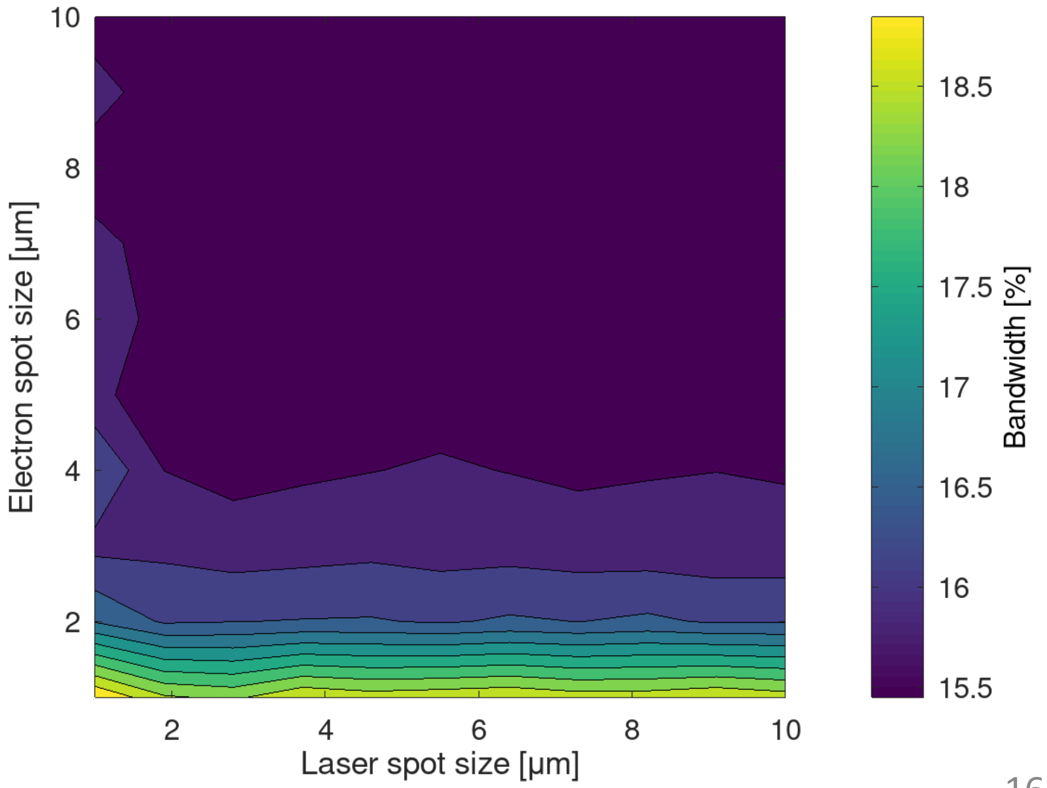
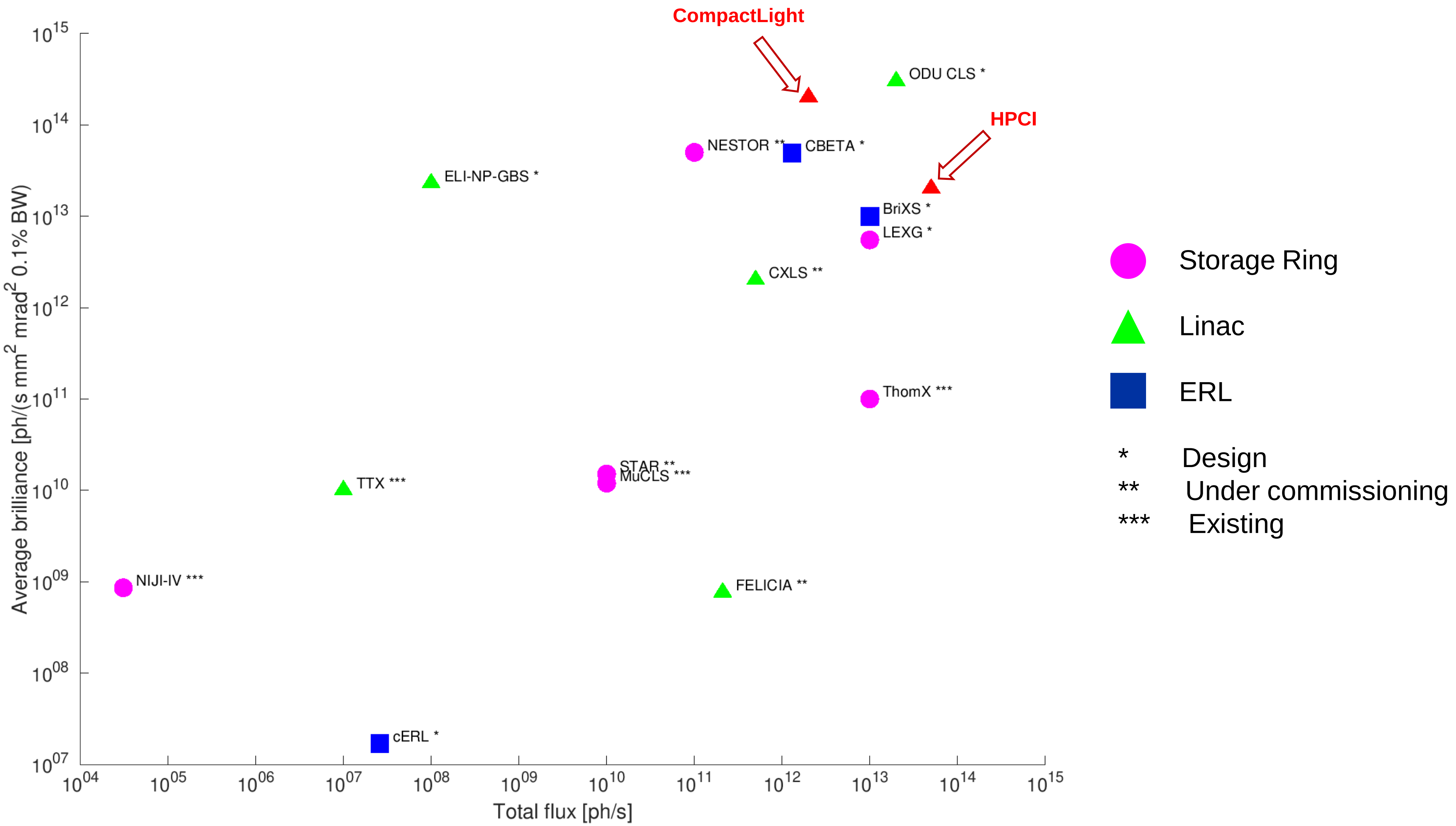




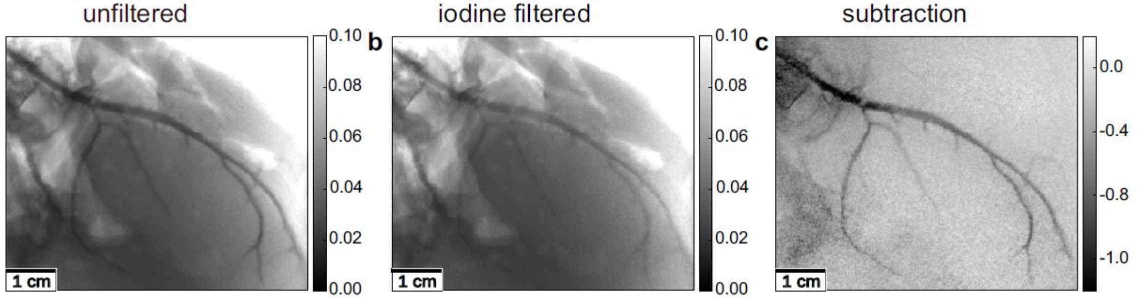
Final beam parameters

Parameter	CompactLight	HPCI	Units
	Quantity		
Bunch repetition frequency, f	1	10^{-2}	kHz
Nb of bunches per train	50	1000	
Effective repetition frequency, f	50	10	kHz
Bunch length, σ_z	1	1	ps
Bunch charge, Q_{pc}	200	300	pC
Bunch spacing	5	2/3	ns
Normalised emittance, $\epsilon^N_{x,y}$	0.3	5	mm mrad
Electron spot size, $\sigma_{x,y}$	2-4	6-11	μm
Laser pulse energy	50	6.6×10^3	mJ
Pulse length, τ	0.6	0.6	ps
Wavelength, λ	1000	1000	nm
Laser spot size, w_0	3-6	3-6	μm
Total flux, $\mathcal{F}$	2×10^{12}	5×10^{13}	ph/s
Average brilliance, $\mathcal{B}$	2×10^{14}	2×10^{13}	ph/(s mm^2 mrad^2 0.1% BW)

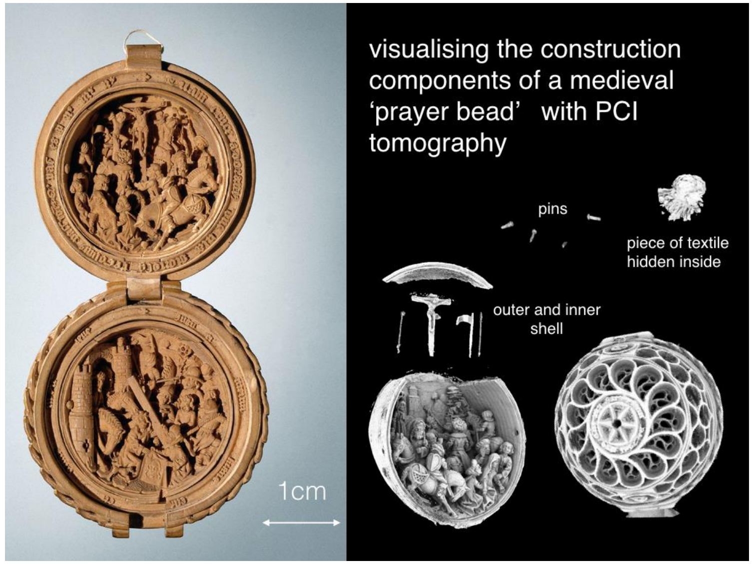
Landscape of ICS sources



Potential applications



- 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 energy x rays, similar to the ones in synchrotron sources.
- Tomographies in particular have already been extensively studied, with proof of concepts 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
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	-	-

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 HPCI therapy and nuclear waste management

	Total flux 10^{11}ph/s	Average brilliance [a]	Flux (1.5 mrad cone) 10^{11}ph/s	BW (1.5 mrad cone) %
XLS (300 MeV)	20	2000	1-14	15-20
HPCI (300 MeV)	500	200	10-150	20-50
XLS (100 MeV)	21	211	1.5-3	4-12
HPCI (100 MeV)	452	26	10-30	20-50

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

Acknowledgements

I would like to thank

- Andrea Latina for his supervision of the project.
- Roberto Corsini, Steffen Doebert and David Alesini for discussions on the electron beam parameters based on XLS and HPCI.
- Edu Granados for suggesting the use of a laser based on TRUMPF’s Dira 1000, and performing simulations for the potential laser pulse energies.

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	
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		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	

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.

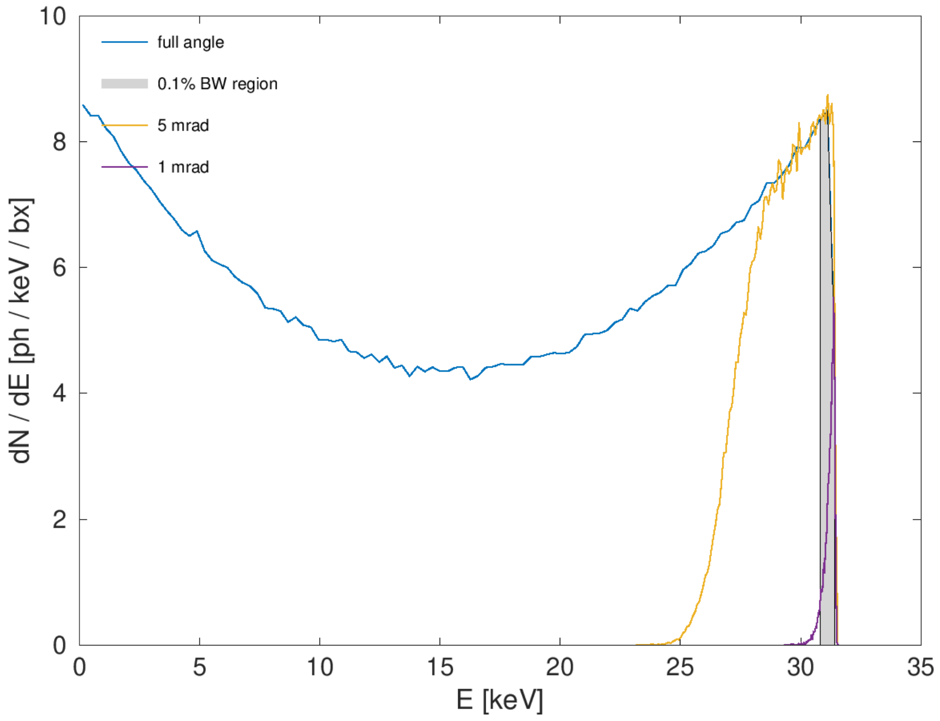
```
%% Define laser-beam IP region
FP = LaserBeam(); % Fabry-Pérot resonator
FP.pulse_energy = 62e-3; % mJ, laser pulse energy
FP.pulse_length = 10; % ps, laser pulse length
FP.wavelength = 1064; % nm, laser wavelength
FP.set_direction(sind(180-X_angle), 0, cosd(180-X_angle)); % depends on crossing angle
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

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

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]

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

- 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],

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

- $\sigma_{i'}$ 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

Bandwidth

- For head-on collisions through a small aperture for regime where recoil is negligible [1],

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

- Contribution from small aperture,

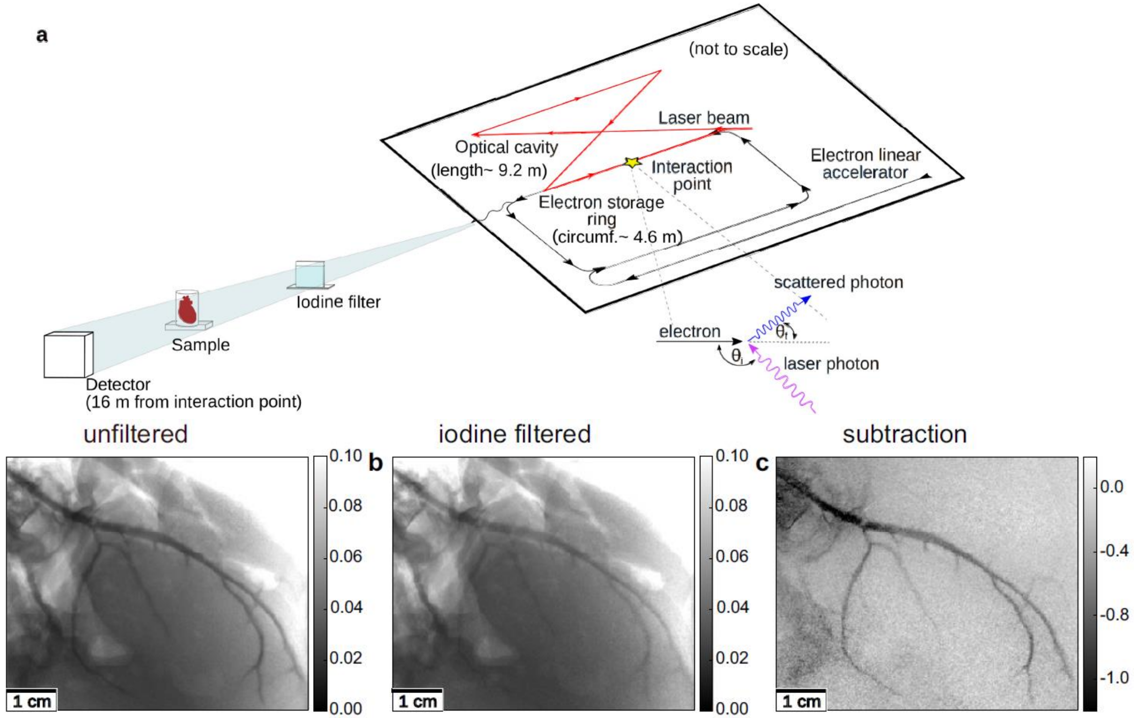
$$\frac{\sigma_{E_\theta}}{E_\theta} = \frac{1}{\sqrt{12}}\frac{\gamma^2\theta^2}{1+\gamma^2\theta^2/2}$$

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

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

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.

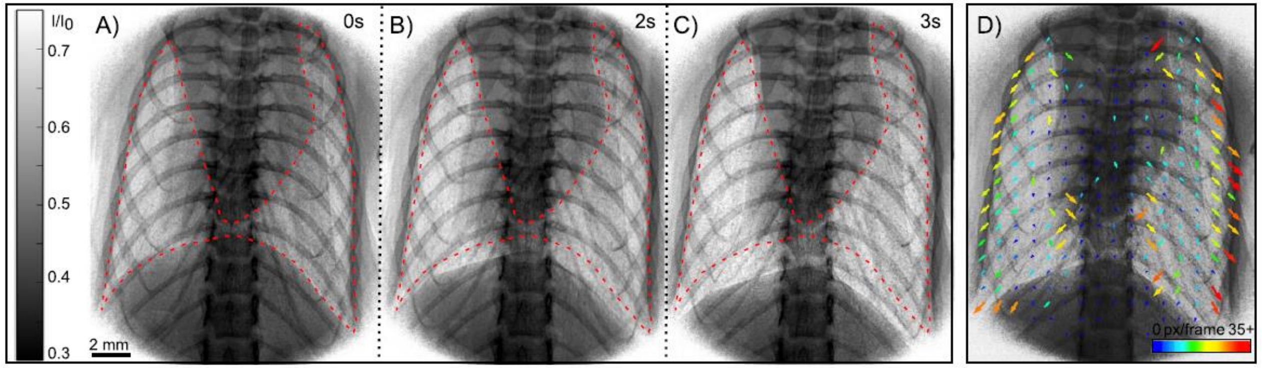


Ref: Kulpe, S., et al. (December 10, 2018). K-edge subtraction imaging for coronary angiography with a compact synchrotron X-ray source. *Plos One, 13,* 12.)

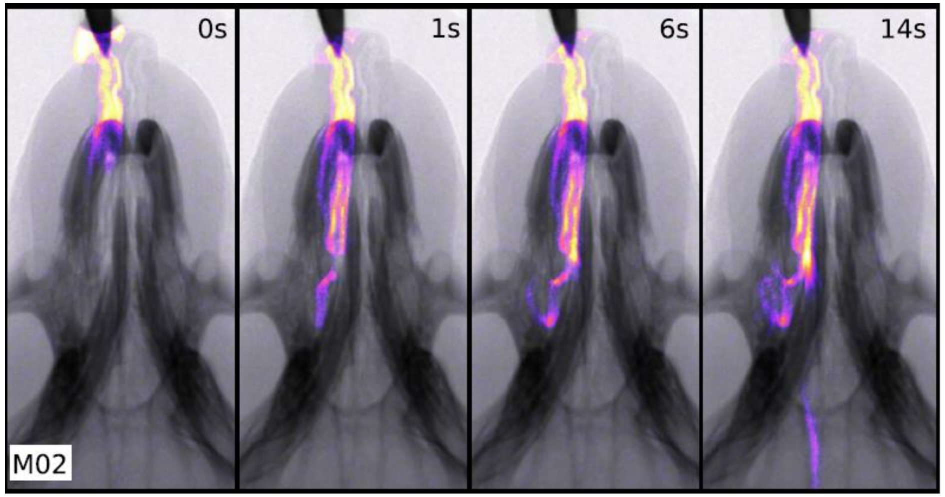
Name	Value	Units
Energy	33.7	keV
Total flux	3×10^{10}	ph/s
Bandwidth	4.5	%
Source size (at IP)	45	μm
Source size (at sample)	16	mm
Divergence	4	mrad

[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.



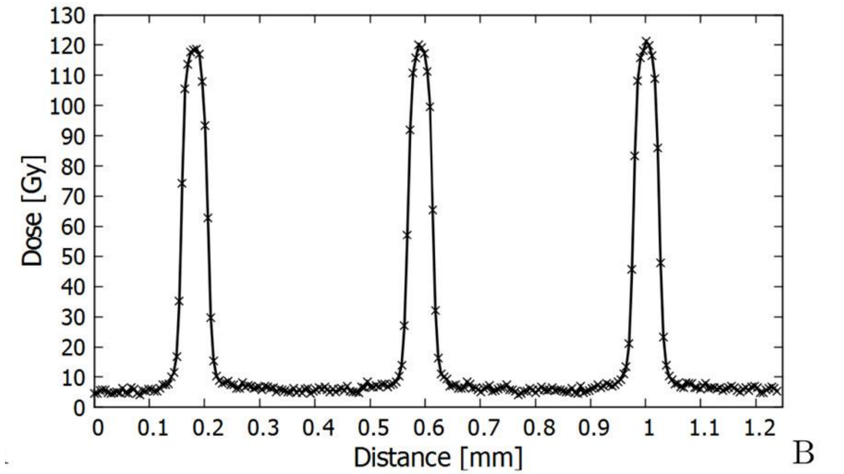
Ref: Gradl, R., et al., SpringerLink (Online service). (2018). In vivo Dynamic Phase-Contrast X-ray Imaging using a Compact Light Source. (Scientific reports.)

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., 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]



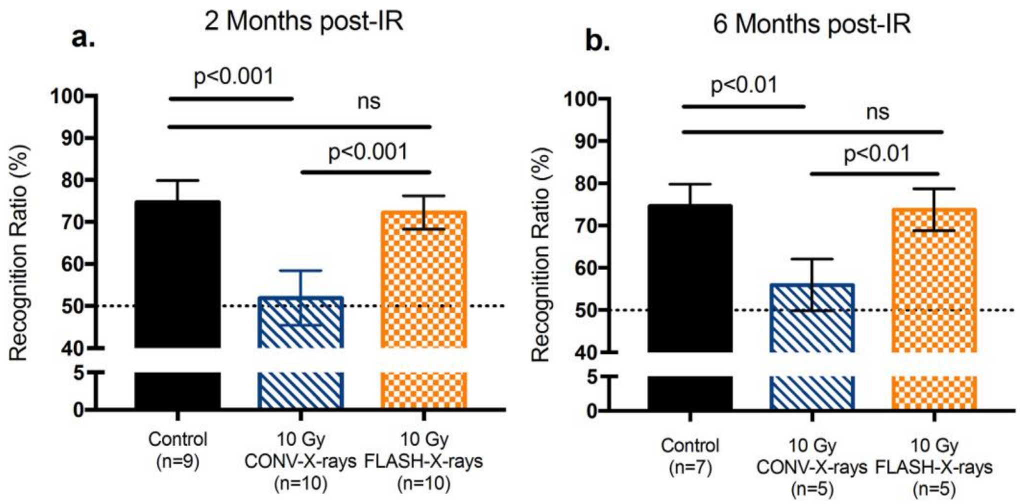
Ref: Stefan, B., et al. (January 01, 2020). Technical advances in x-ray microbeam radiation therapy. *65,* 2.)

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 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.

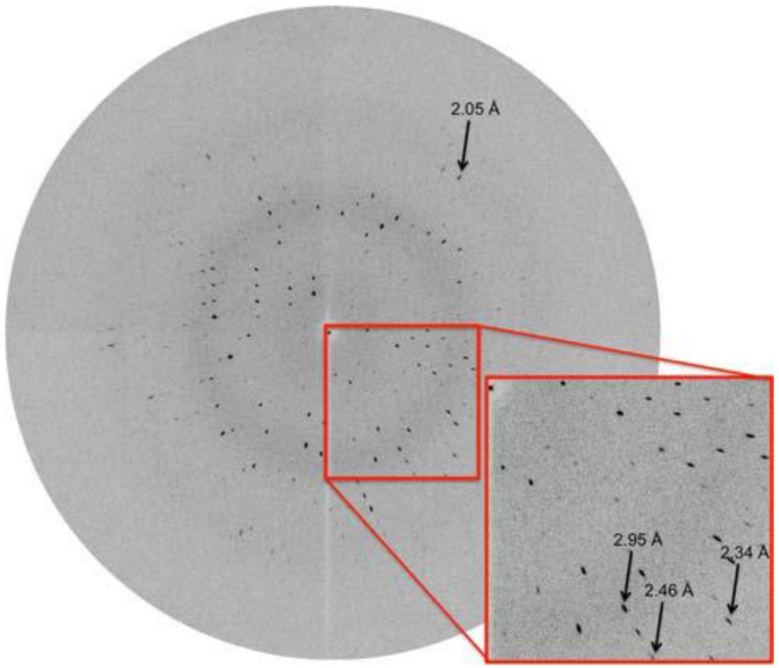
Name	Value	Units
Energy	102	keV
Total dose	10	Gy
Total flux	1.33×10^{14}	Ph/s
Source size (at IP)	50	µm

[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	$\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].

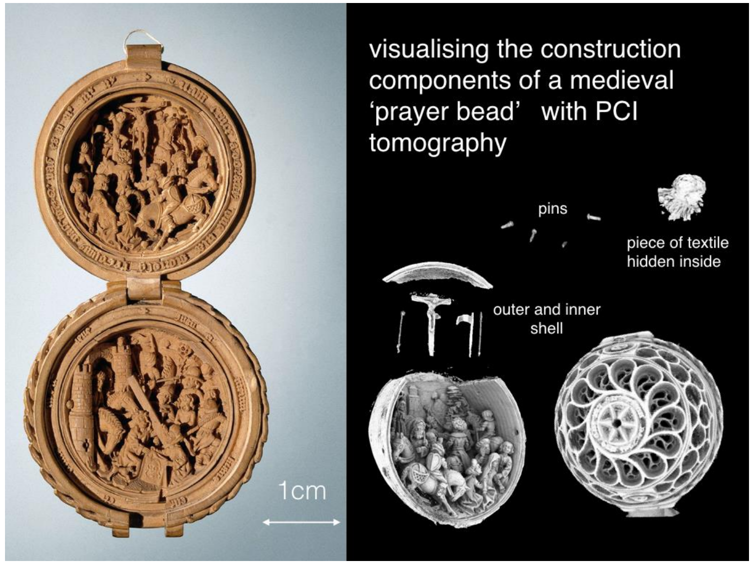


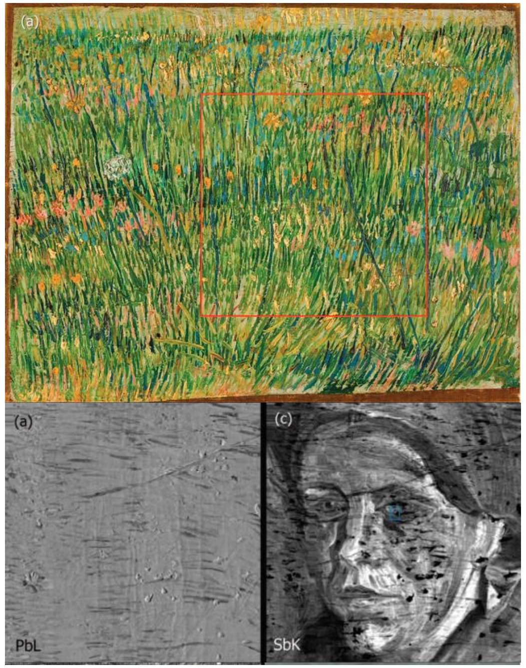
Ref: Abendroth, J., et al. (January 01, 2010). X-ray structure determination of the glycine cleavage system protein H of Mycobacterium tuberculosis using an inverse Compton synchrotron X-ray source. Journal of Structural and Functional Genomics, 11, 1, 91-100

[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].





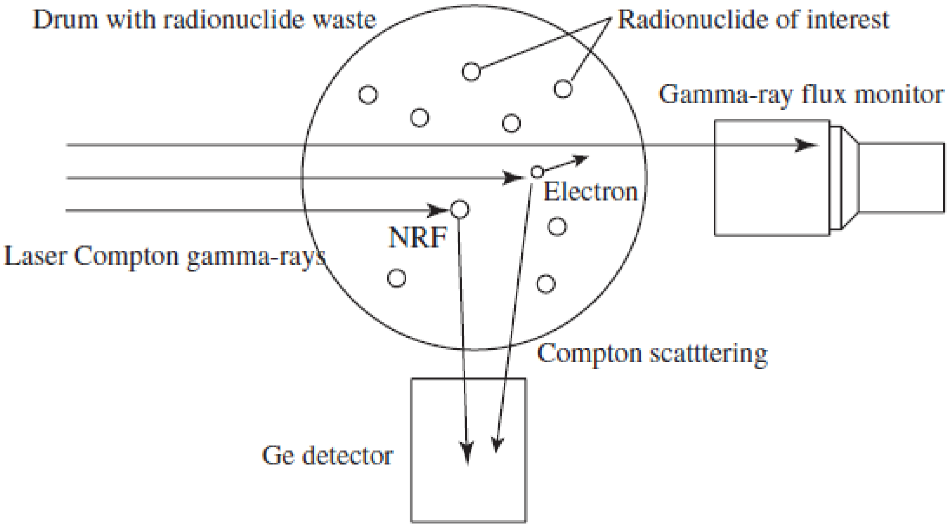
Requirements table for the analysis techniques used in heritage studies.

	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.