Inverse Compton X-ray Source for 3D Nanostructured Metrology

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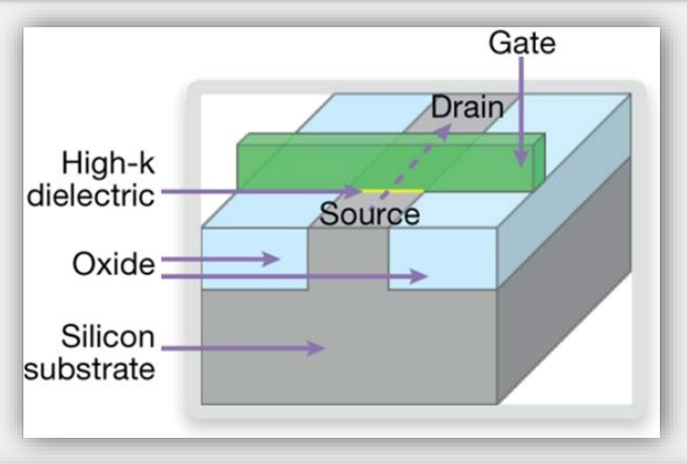
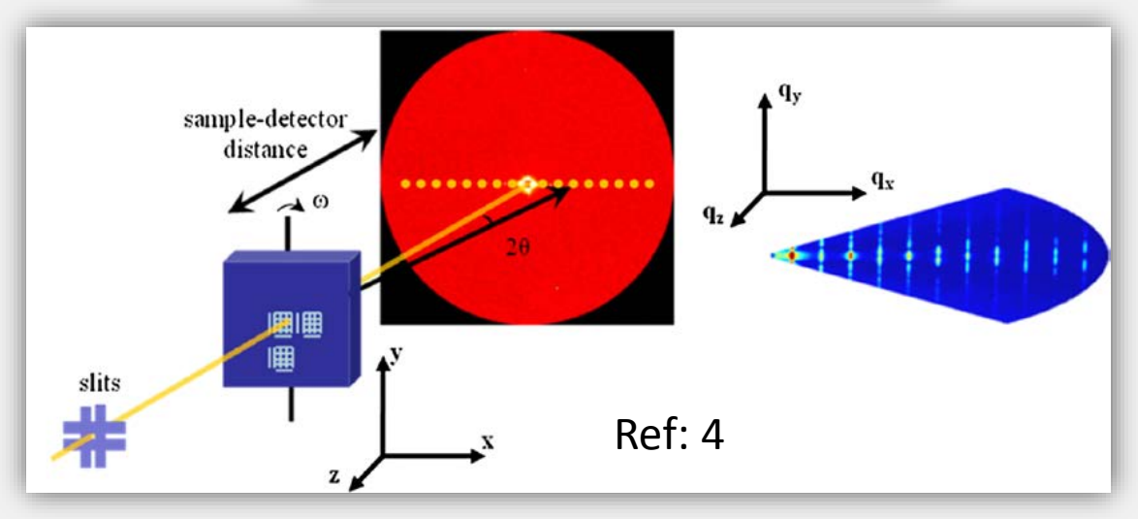
Background

As the semiconductor industry continues into the nanoelectronics era following Dennard scaling law, with half-pitch values decreasing below 10 nm, one of the significant challenges lies in the metrology of nanoelectronic devices and 3D interconnect architectures at these sub-nanometer domains [1]. In order to optimize 3-D in-line metrology of critical dimension (CD) geometries for various nanoelectronic applications, non-destructive rapid feedback monitoring system with angstrom resolution [2] is required. One grand challenge for CD-SAXS x-ray sources is meeting both the x-ray energy and flux criteria (similar to a Synchrotron) while maintaining laboratory size. Other problems with x-ray sources include: *lack of x-ray energy exceeding 20 keV, low photon number, large beam size, and long scan time.* Currently, no x-ray source has been able to solve this problem.

3D architecture of nanostructured devices includes: The ability to discern in-line topology of FinFET height and pitch, DRAM pitch, copper wire pitch, low-*k* dielectric thickness, and interfaces and nano-structures. 3D nanostructured devices create 2D diffraction patterns with features discernible through small-angle x-ray scattering





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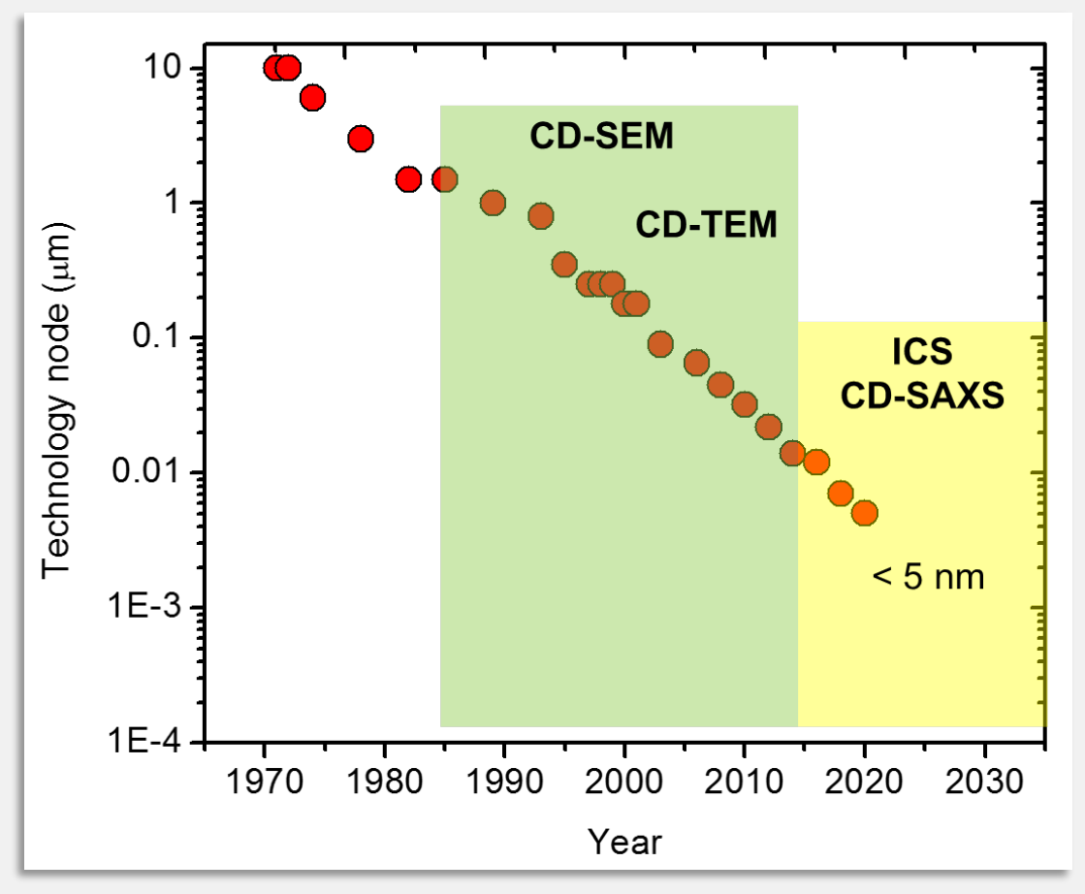
List of needs for semiconductor nanostructures [1,3]

Nanostructure Type	CD [1-2] (nm)				X-ray Energy (keV)	Photon Flux (Ph/s)	Beam Size (um)
	2017	2019	2021	2023			
Si FinFET Half-pitch	19	15	12	9.5	20-70	10^{10}	< 100
High-k FinFET fin width	6.8	6.4	6.1	5.7	20-70	10^{8}	< 100
Cu wire pitch	25	20	15.9	12.6			
Low-k pore size	5	3	1	<1	20	10^{12}	< 5
Photoresist mask size	13	13	< 10	< 10	20	10^{10}	<10
3D tomography of Cu vias and sodder joints	<100	<50	<50	<25	>100	10^{12}	< 10



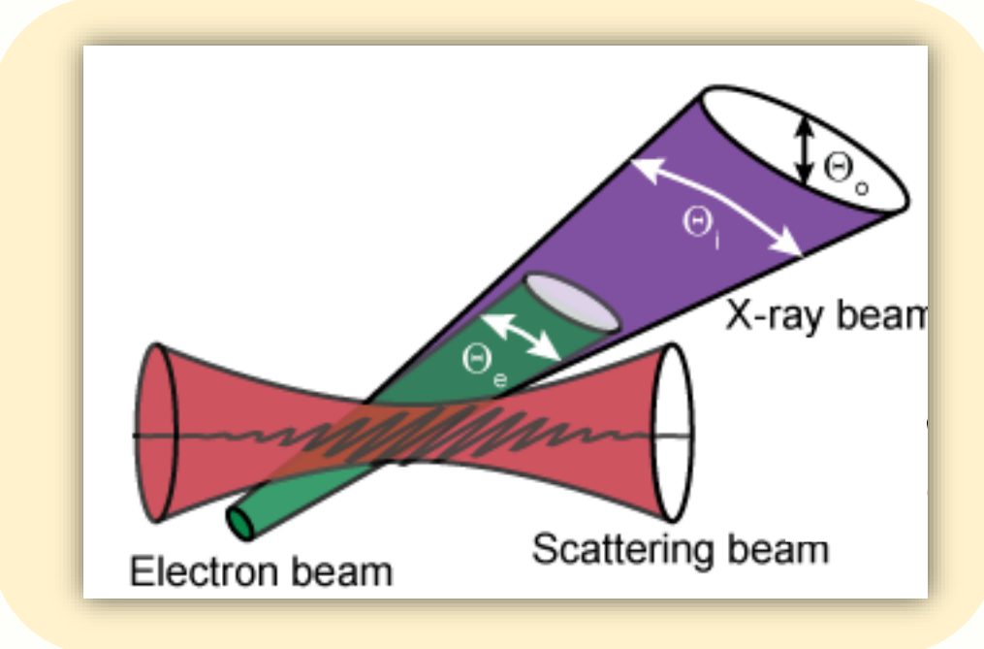
All-laser based Compton x-ray source can meet the requirements for semiconductor metrology

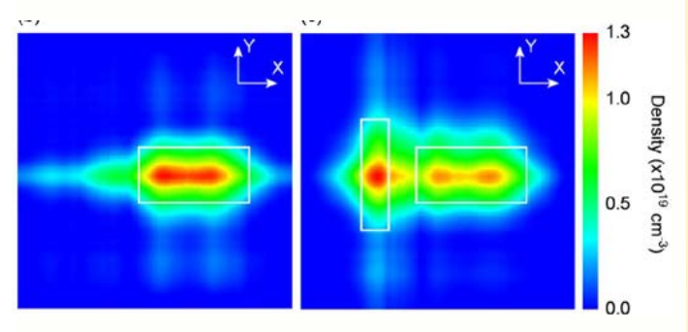
- A viable solution to the CD-SAXS source problem is using all laser-based Inverse Compton scattering (ICS) x-ray source [5, 6].
- Compton scattering utilizes the double Doppler shift from relativistic electrons to create x-rays from visible light. The maximum photon energy is $E_\gamma = 4\gamma^2\hbar\omega_L$, where γ is proportional to the kinetic energy of the electrons ($E_e = \gamma mc^2$) and ω_L is the frequency of the laser
- All-laser driven ICS at UNL has demonstrated high brightness, high tunability, low spot size, and laboratory size beamline of < 50 m² [5]. Using all laser-based system leads to a compact and tunable accelerator that is synchronized to the scattering laser beam.

CD-SAXS Beamline Design

Inverse Compton Scattering

High-power laser drives a high-energy electron accelerator. Another pulse from the same laser scatters off the electron beam in a head-on collision and produces a beam of x-rays





Specs of ICS source for SAXS Beamline

Total Lab Size: < 50 m²
Beamline length: 2 m

LASER

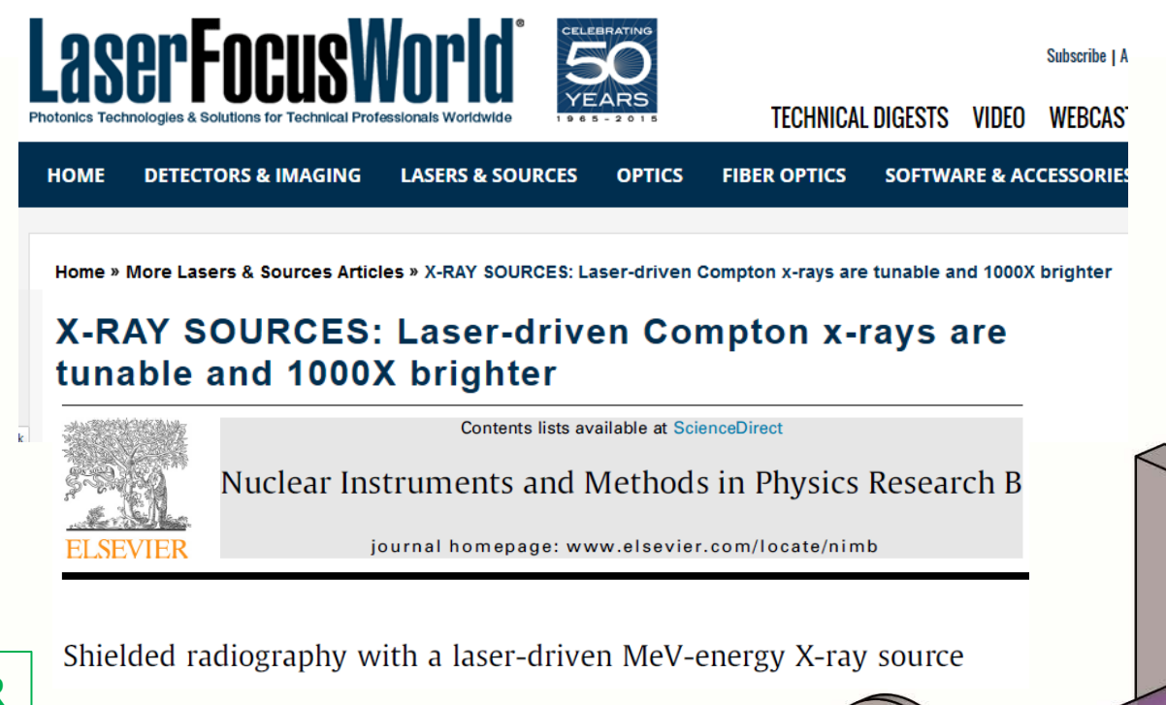
Laser power: 100 W – 1 kW
Peak Power: 50 TW
Duration: 30 fs
Focused spot size: 20 μm

ACCELERATOR

Electron energy: 10 – 100 MeV
Beam current: 1-10 nA
Electron beam size: 10 μm
Electron duration: 10 fs

X-RAYS

X-ray Photon number: $10^8 – 10^{10}$ s^{-1}(1% BW)
Photon energy: 8-70 keV
Beam size at source: 5-10 μm
Pulse duration: 10-30 fs
q-range: 0.7-8.1 Å⁻¹



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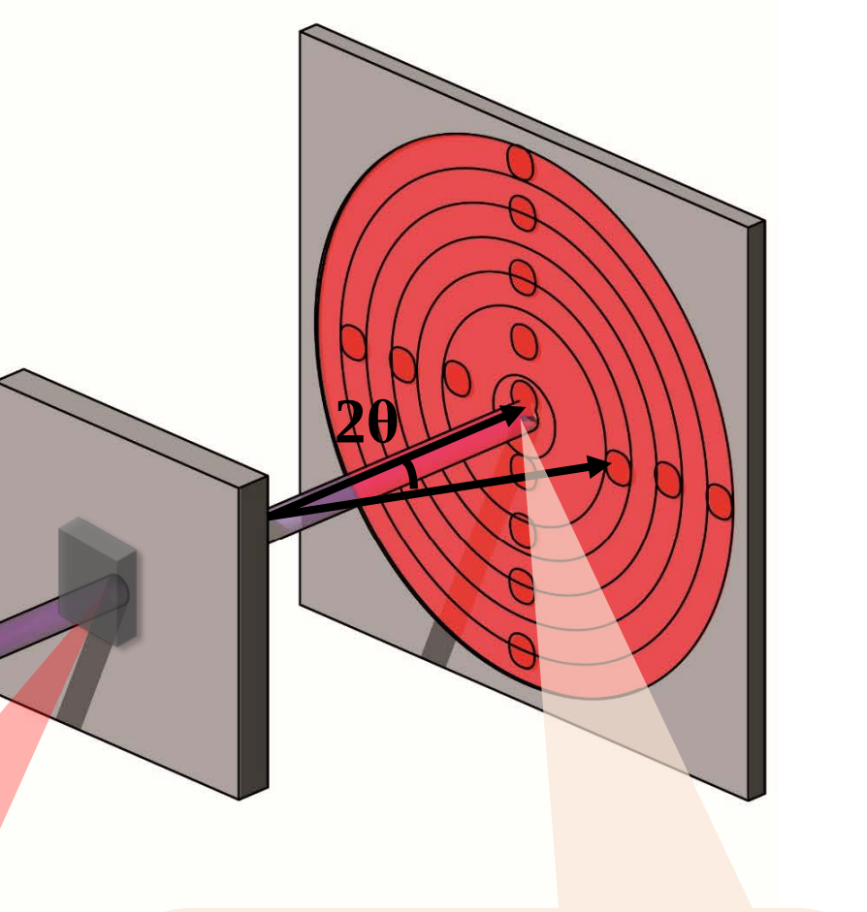
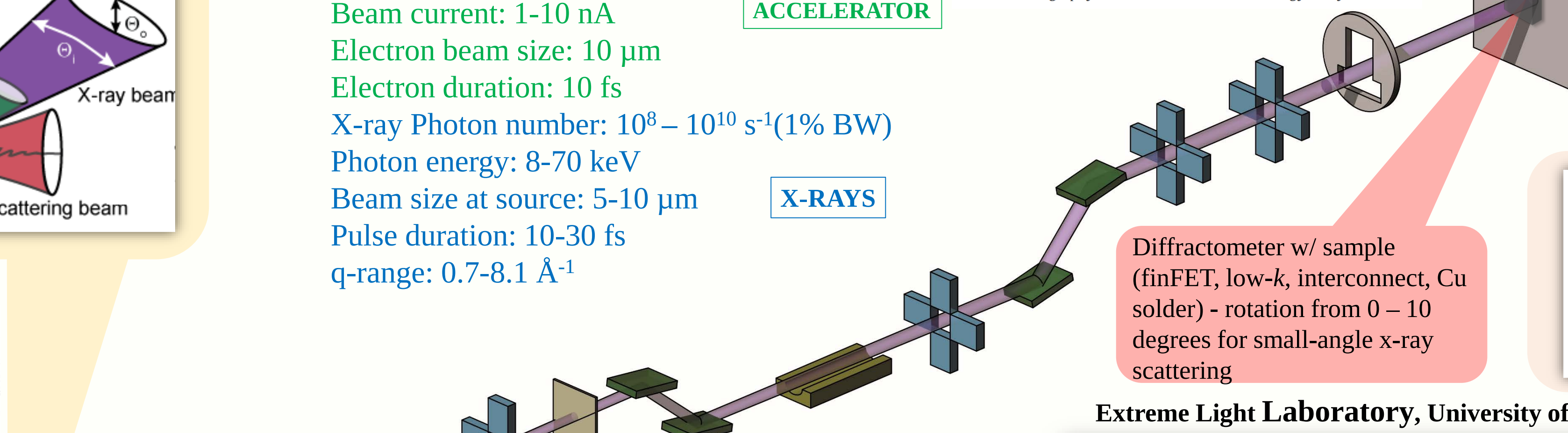
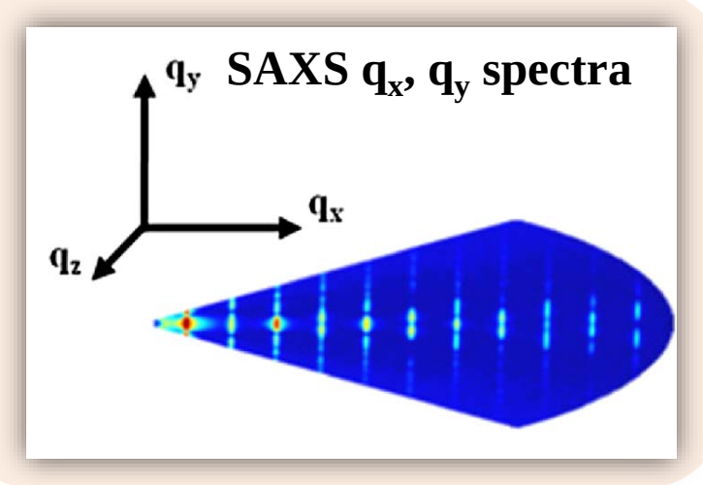
Shielded radiography with a laser-driven MeV-energy X-ray source



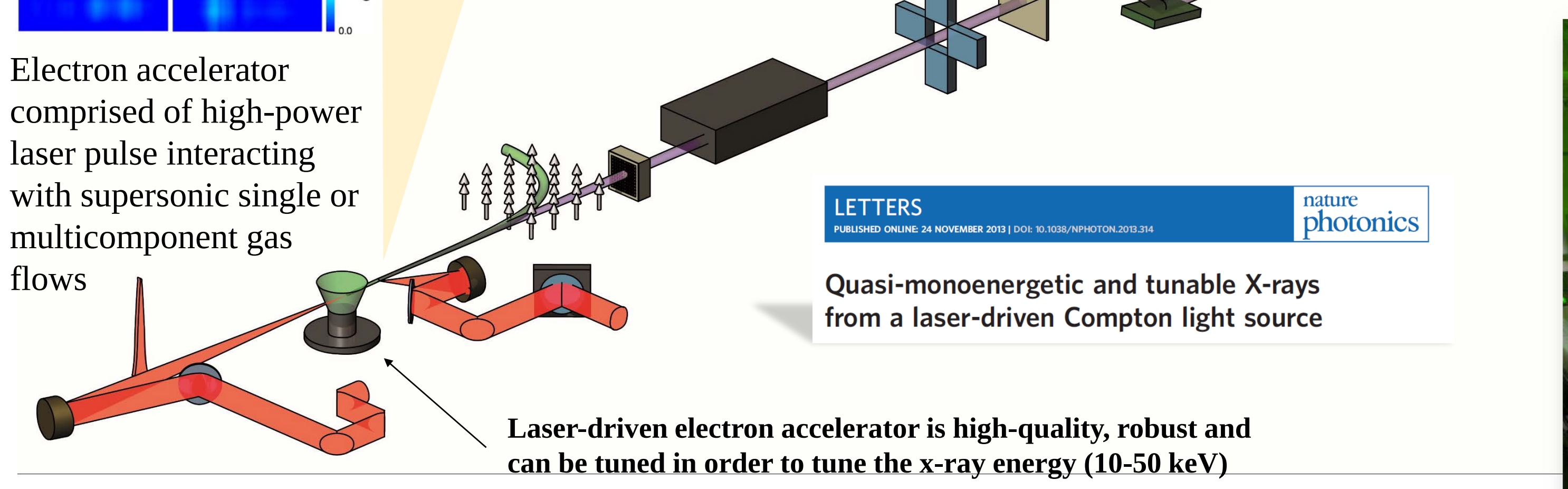


Diffractometer w/ sample (finFET, low-*k*, interconnect, Cu solder) - rotation from 0 – 10 degrees for small-angle x-ray scattering



SAXS q_x, q_y spectra

Electron accelerator comprised of high-power laser pulse interacting with supersonic single or multicomponent gas flows



LETTERS

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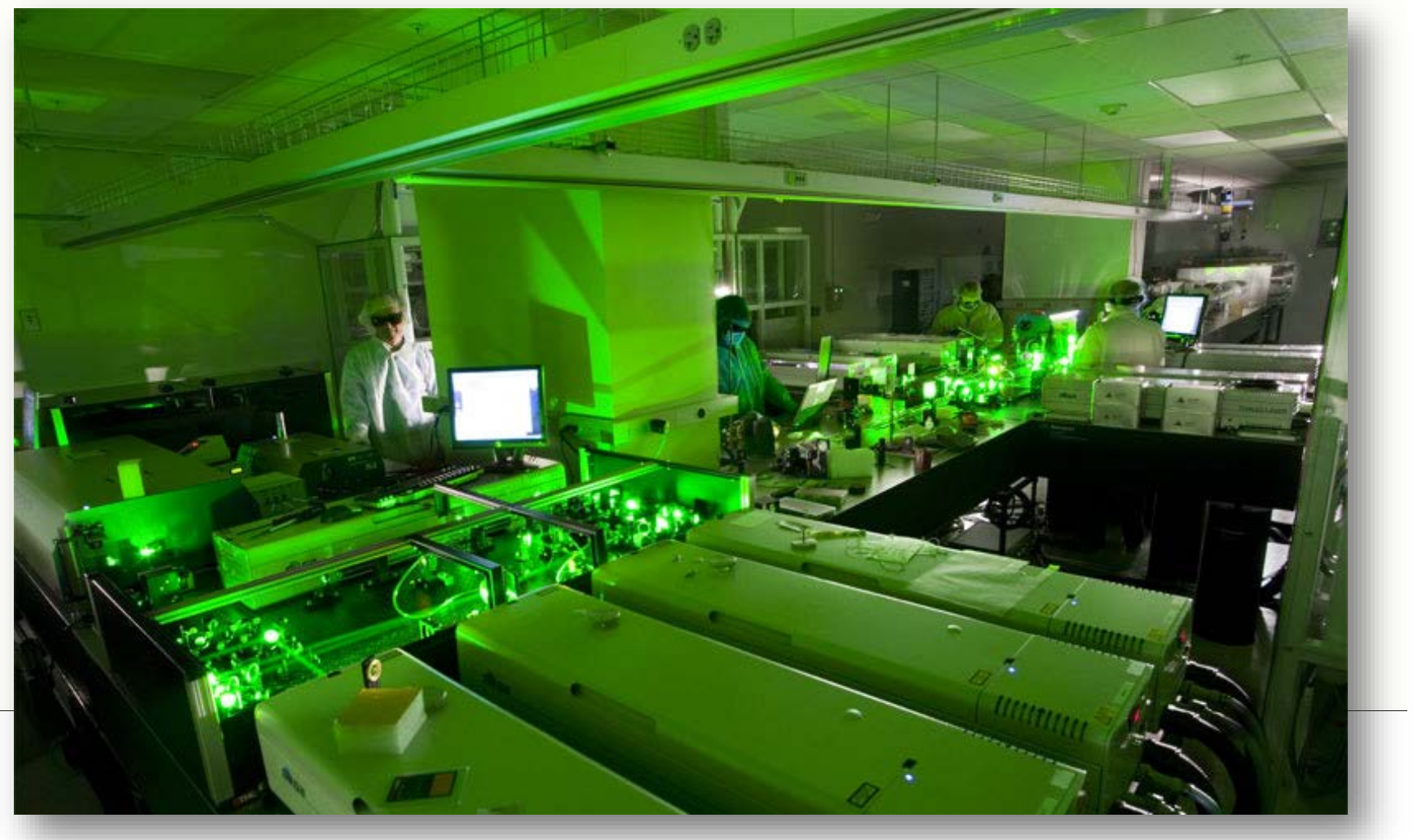
nature photonics

Quasi-monoenergetic and tunable X-rays from a laser-driven Compton light source

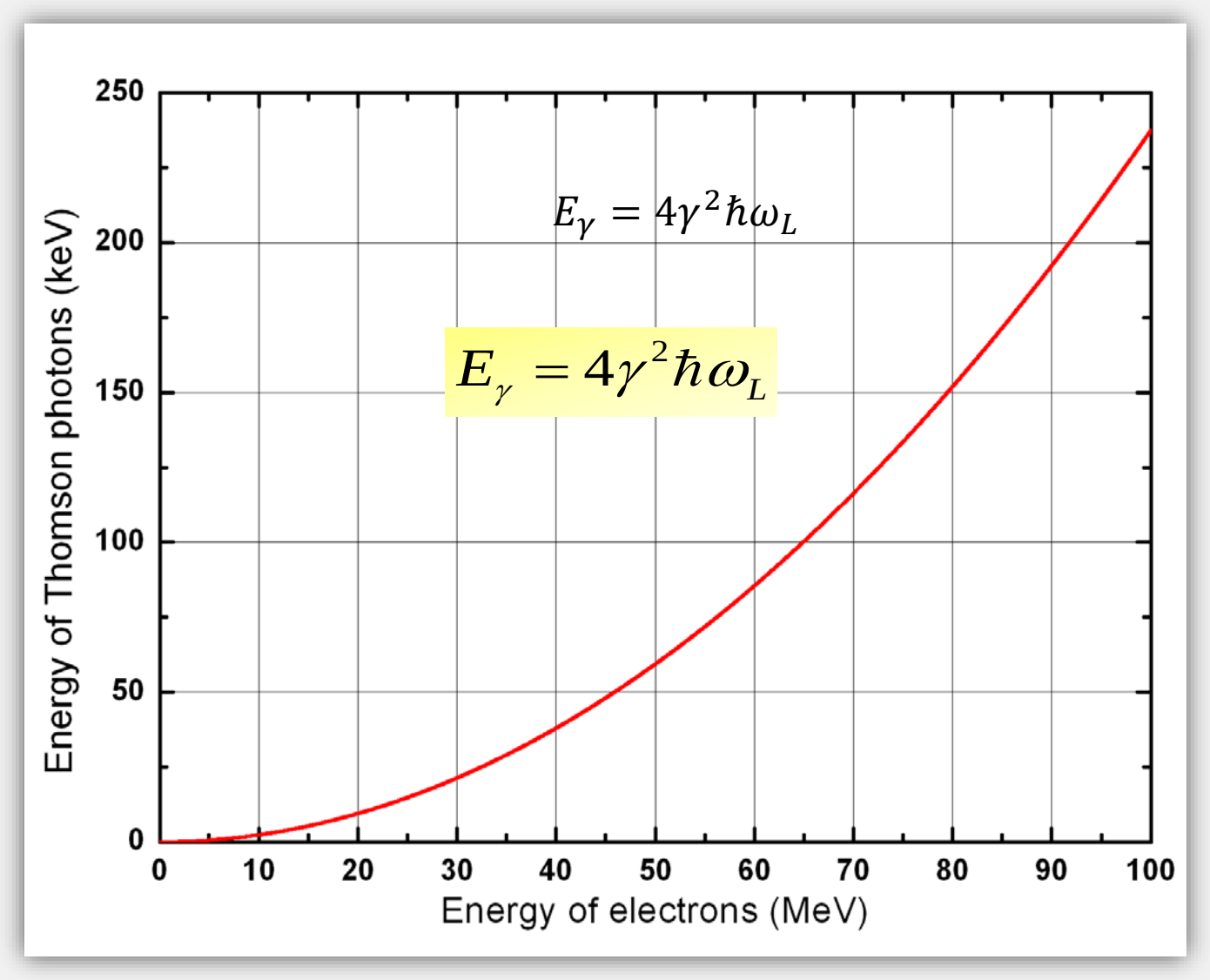
Laser-driven electron accelerator is high-quality, robust and can be tuned in order to tune the x-ray energy (10-50 keV)

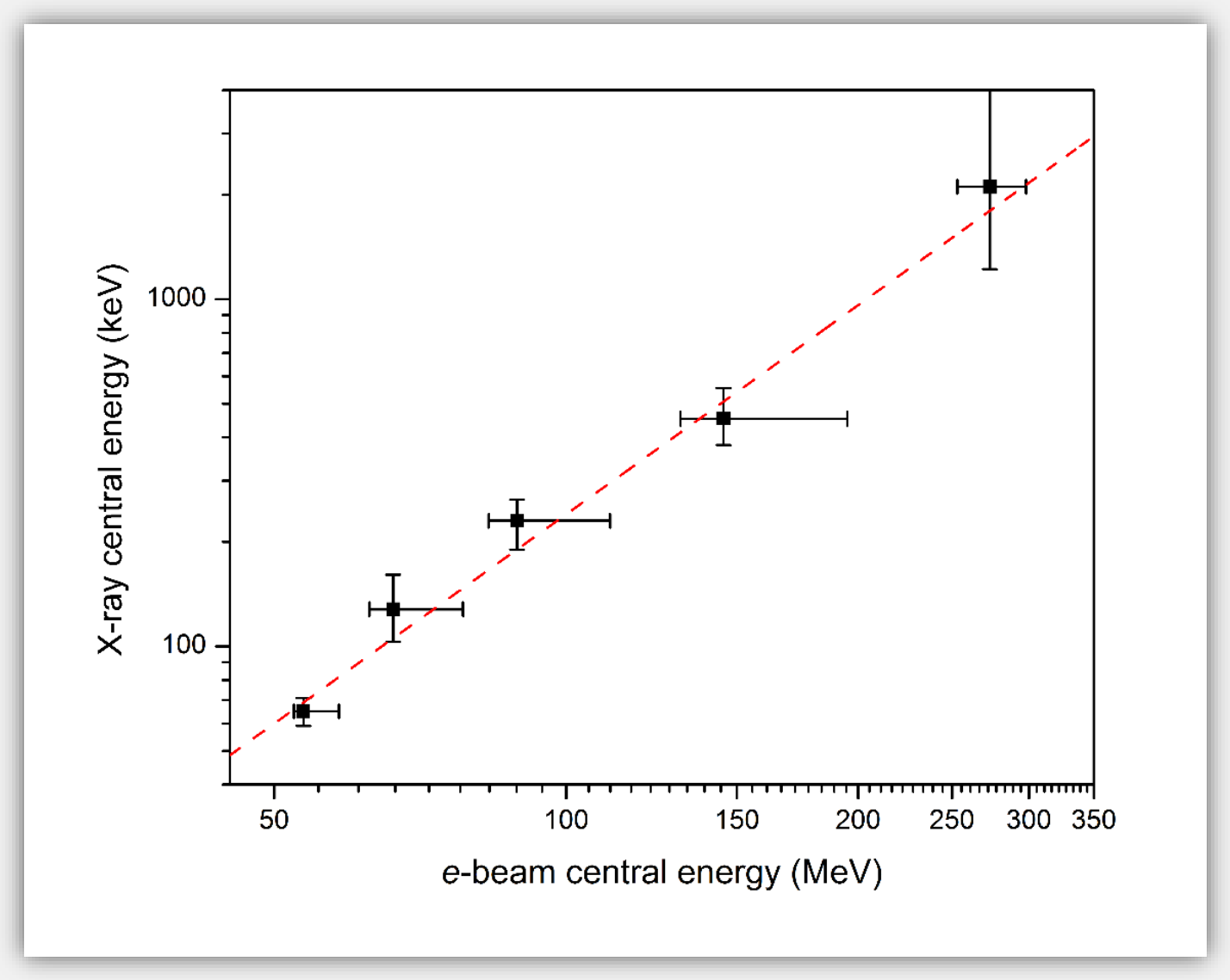
Extreme Light Laboratory, University of Nebraska-Lincoln

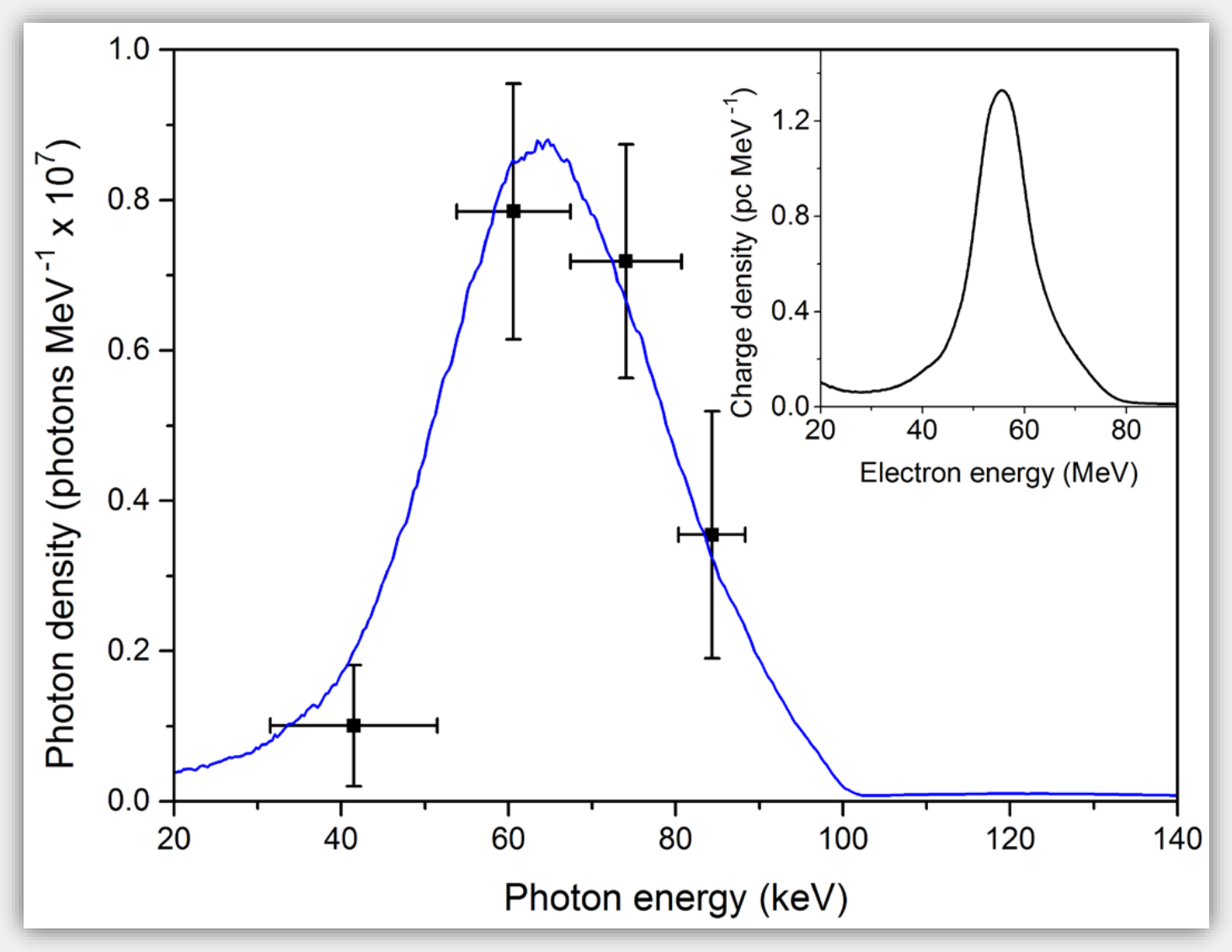


Prior Results

Tunable operation of x-ray source demonstrated in prior work [6]







- Tunable operation of x-ray source is made possible by tunable electron accelerator. Laser driven device can be tuned from 10-100 MeV using a single device and to > 500 MeV using multiple targets. For semiconductor applications single stage x-ray source can be tuned from 10-100 keV.
- Photon number depends on specific configuration and can has been shown to span the range 10^7-10^{10} s^{-1} using current laser system [5,6]. Significant improvements possible by using latest diode pumped high-average power lasers (e.g., Yb:YAG disk laser).

Acknowledgments

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Results and Modeling

We have generated narrowband electron beams using structured targets and optical injection. The energy of the electron beam can be tuned while keeping other parameters such as charge, divergence and energy spread constant. Using this approach we have generated x-ray beams that can be tuned in energy keeping other parameters nearly invariant.

Electron-beam spectrum on scintillator for 12 MeV, 30 MeV, and 47 MeV

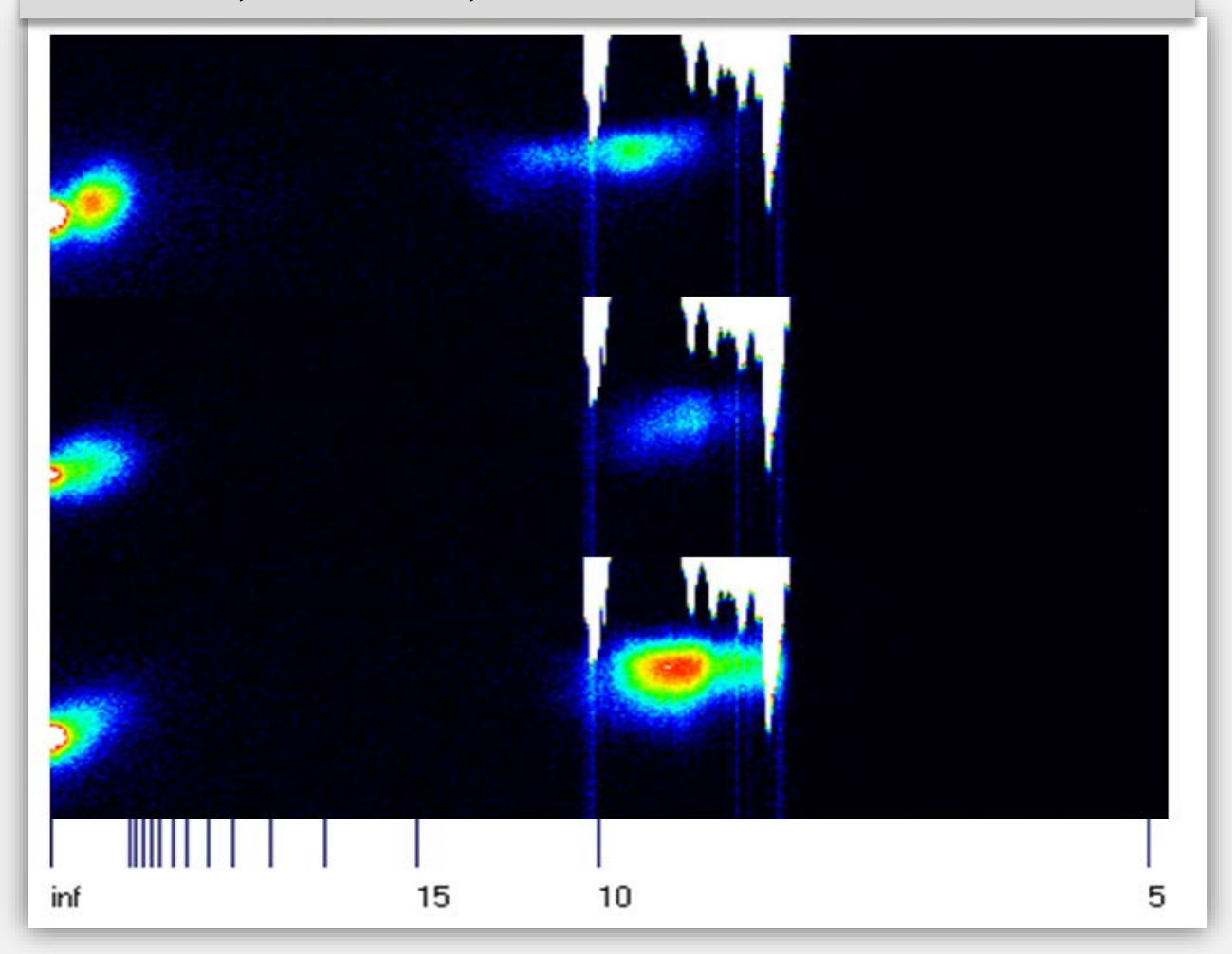
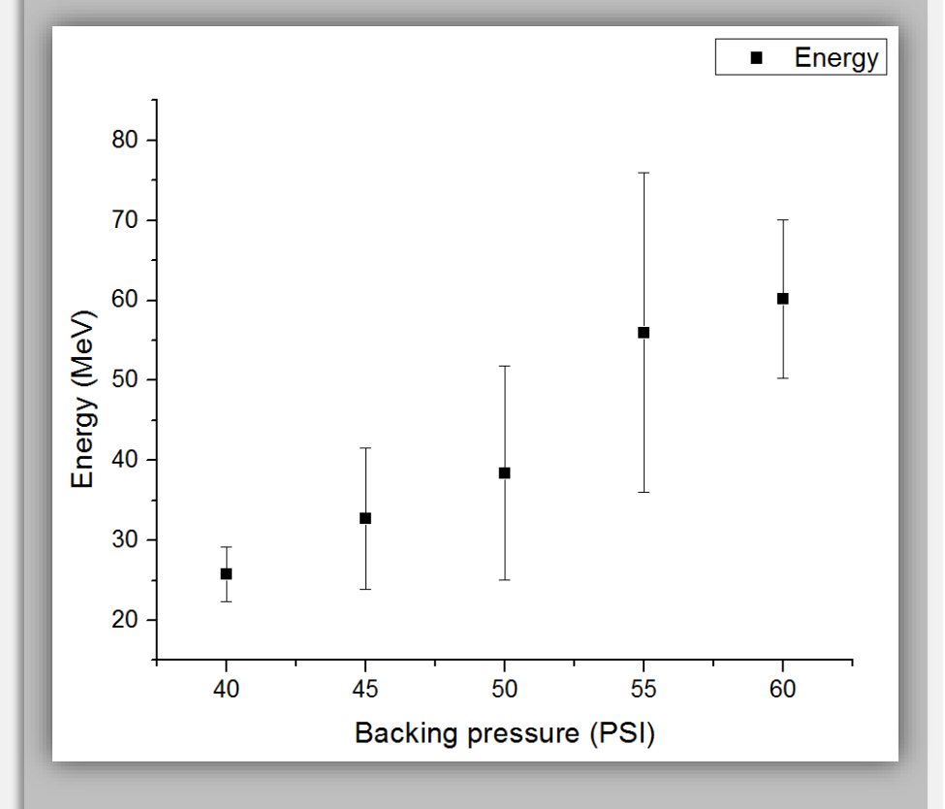


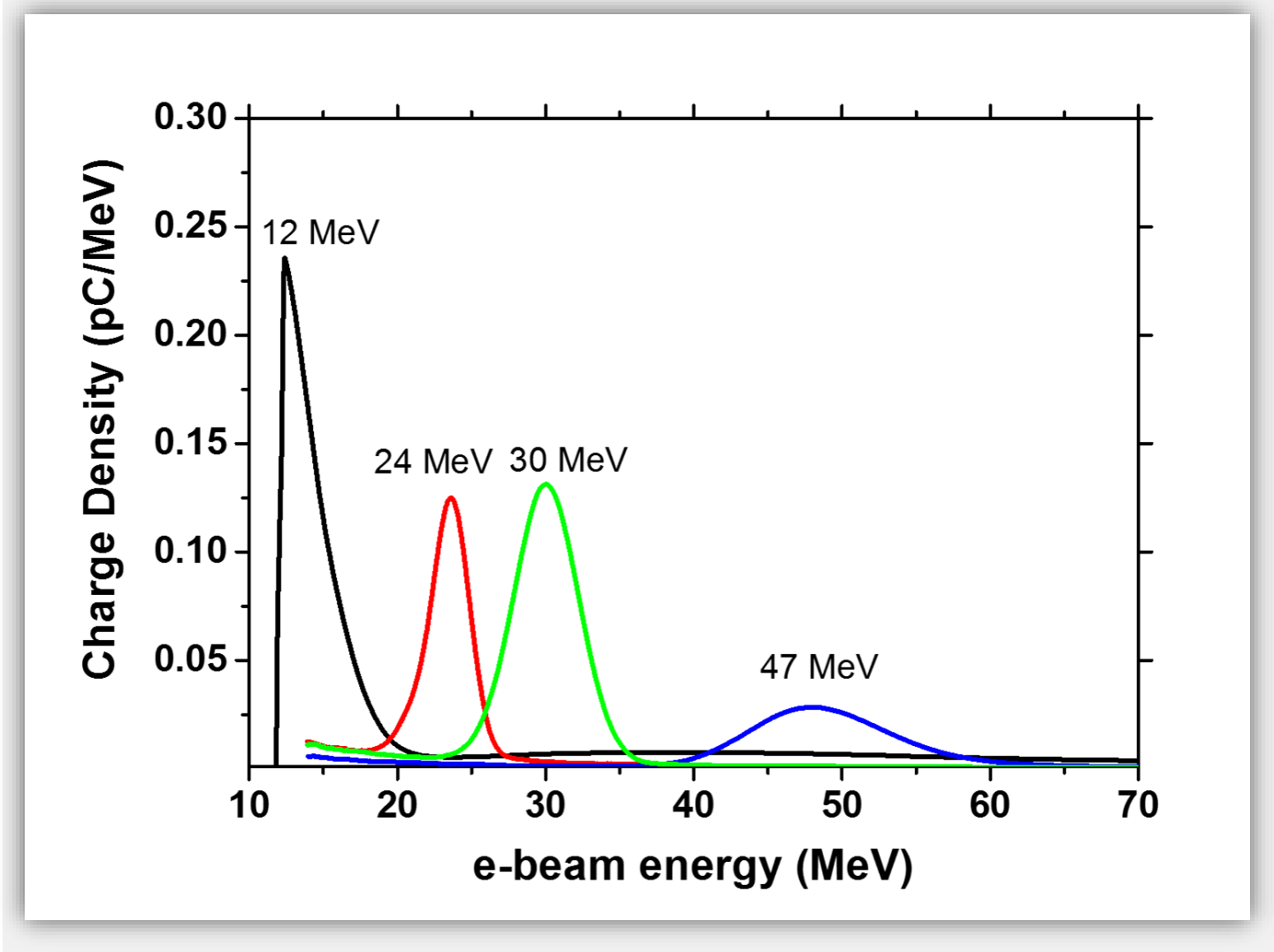
Table of results for the optical injection experiment with 2 mm jet

e-beam Energy (MeV)	Energy spread, MeV (FWHM)	Divergence, mrad (FWHM)	X-ray energy (keV)
12	4.8	4.3	3.4
14	7.1	4.5	4.7
18	2.5	2.8	7.4
24	6.1	1.5	13
30	5.5	3.5	21
36	7.2	1.8	31
48	13.0	2.1	55
57	18.4	0.31	78

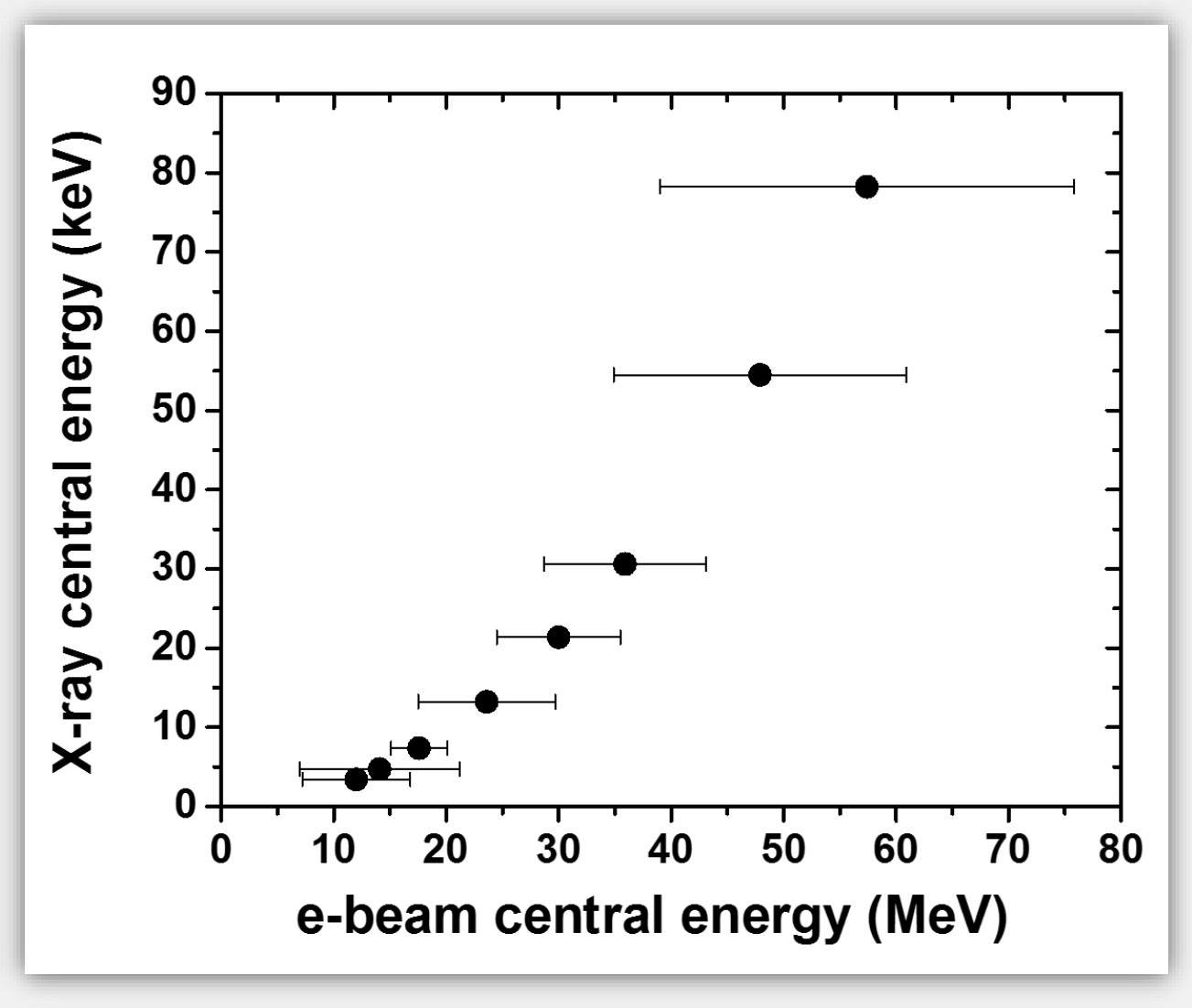
Electron beam can be tuned by changing plasma parameters



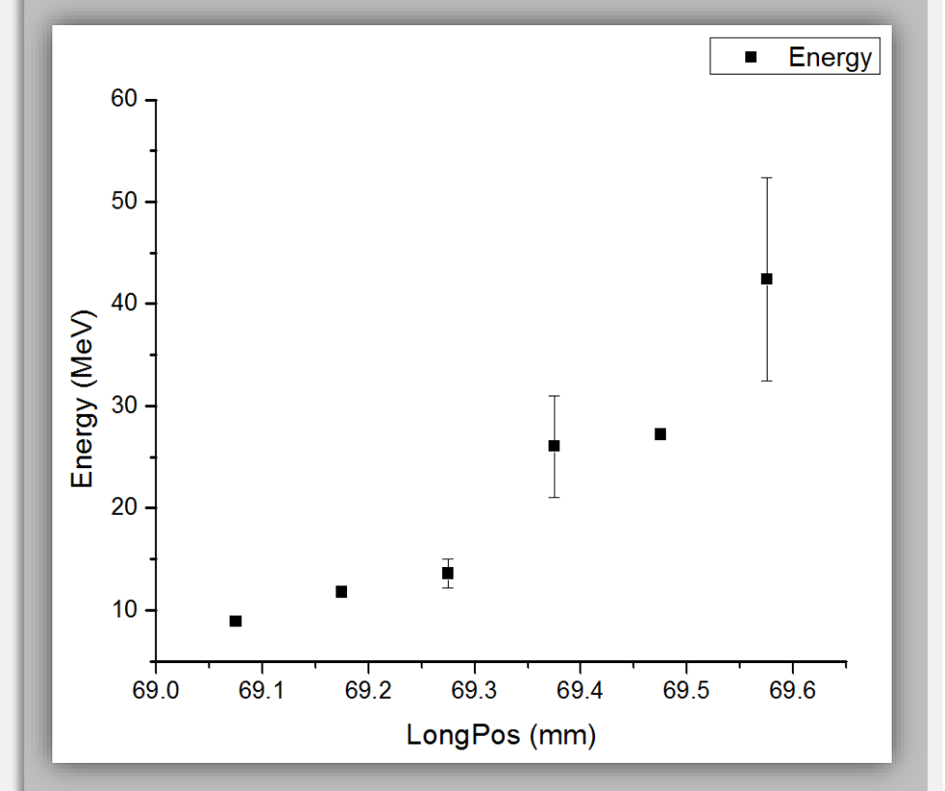
Electron-beam energy as a function of 2 mm jet gas (He) pressure



Charge density as a function of electron-beam energy from Lanex plot for 12 MeV, 24 MeV, 30 MeV, and 47 MeV



Calculated x-ray central energy as a function of measured e-beam central energy from optical injection experiment with the 2mm jet



Electron-beam energy as a function of 2 mm longitudinal scattering and drive beam overlap position inside the plasma

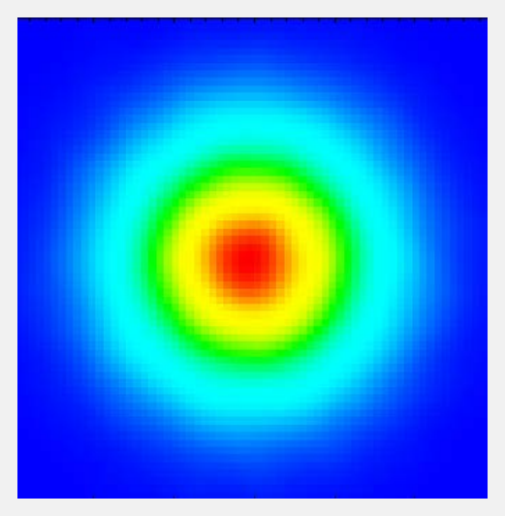
Simulations using a Monte-Carlo code demonstrate source can be scaled to higher fluence for metrology

Laser Parameters used in the simulations

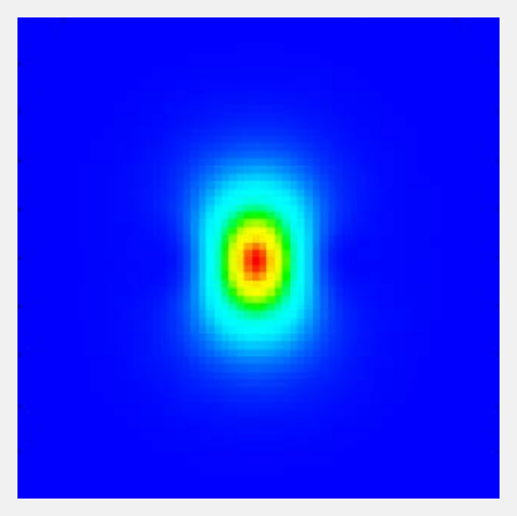
Parameter	Value
λ (nm)	800
Duration (ps)	1
Rayleigh range (mm)	1
a_0	0.3
Interaction angle	0 deg.
Rep rate	1 kHz

Simulation parameter based on 12, 24, 30, and 48 MeV electron beam

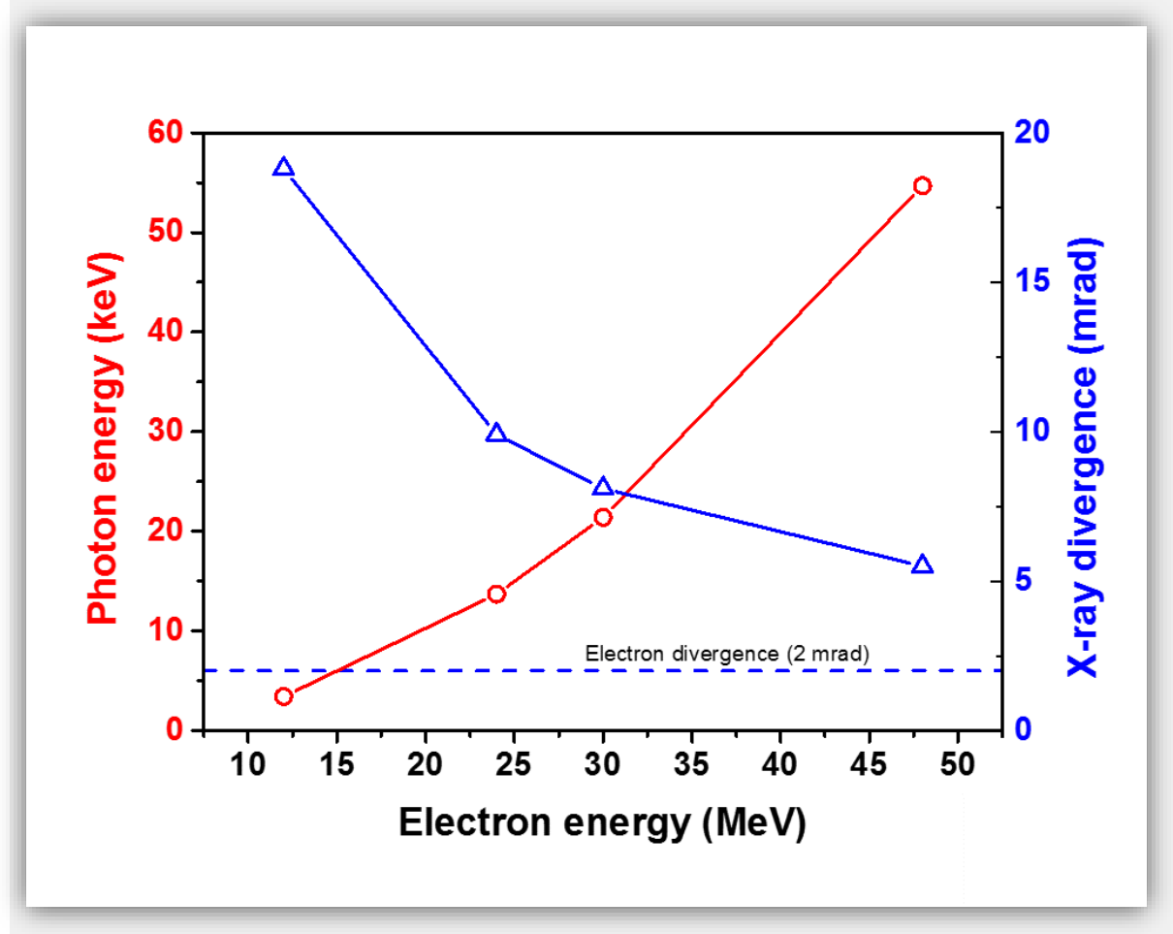
Parameter	Value	Value	Value	Value
Energy (MeV)	12	24	30	48
Spread (MeV)	1.2	1.2	3	4.8
Divergence (mrad)	2	2	2	2
Source size (μm)	10	10	10	10
Duration (fs)	33	33	33	33
β_x	5×10^{-3}	5×10^{-3}	5×10^{-3}	5×10^{-3}
ϵ_x	4.7×10^{-7}	4.7×10^{-7}	1.2×10^{-6}	1.2×10^{-6}
N_e	2×10^{6}	2×10^{6}	2×10^{6}	2×10^{6}



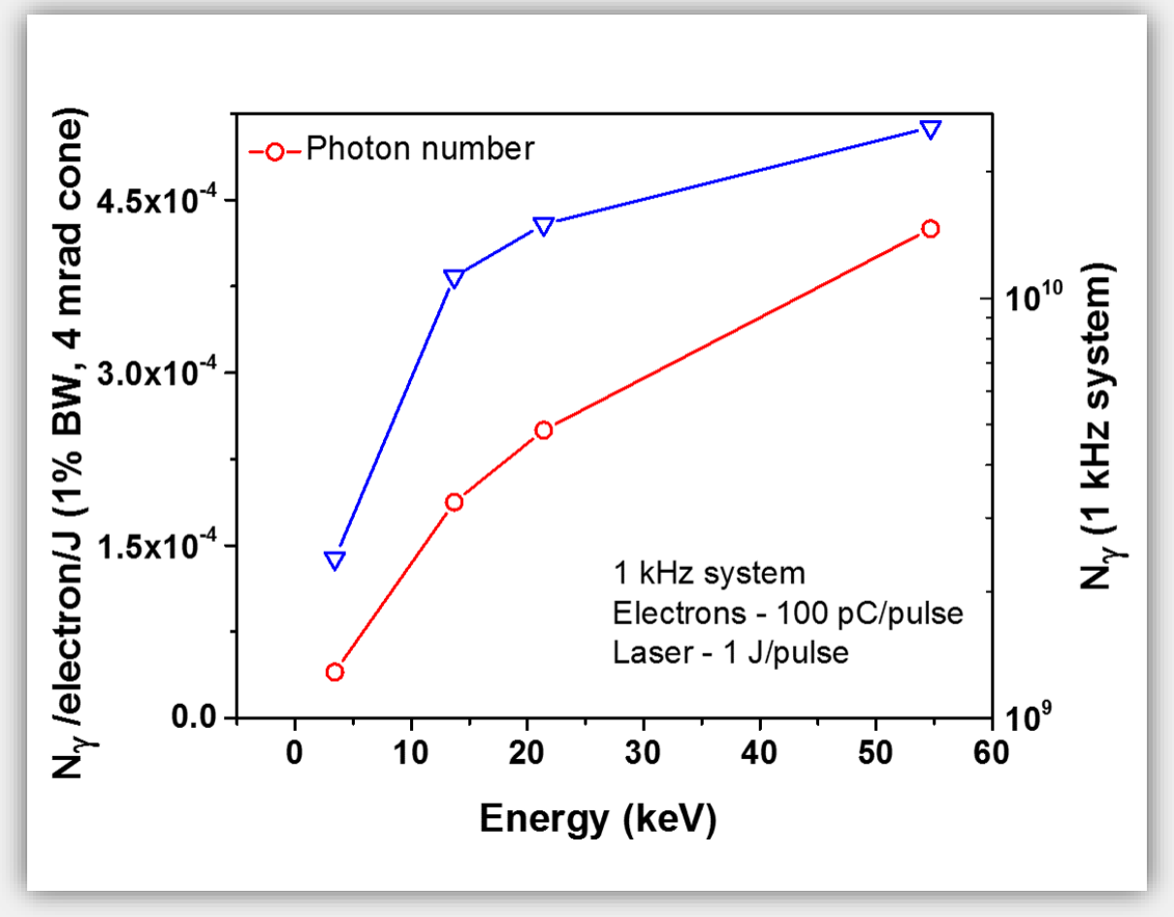
Electron beam at source - 10 μm size



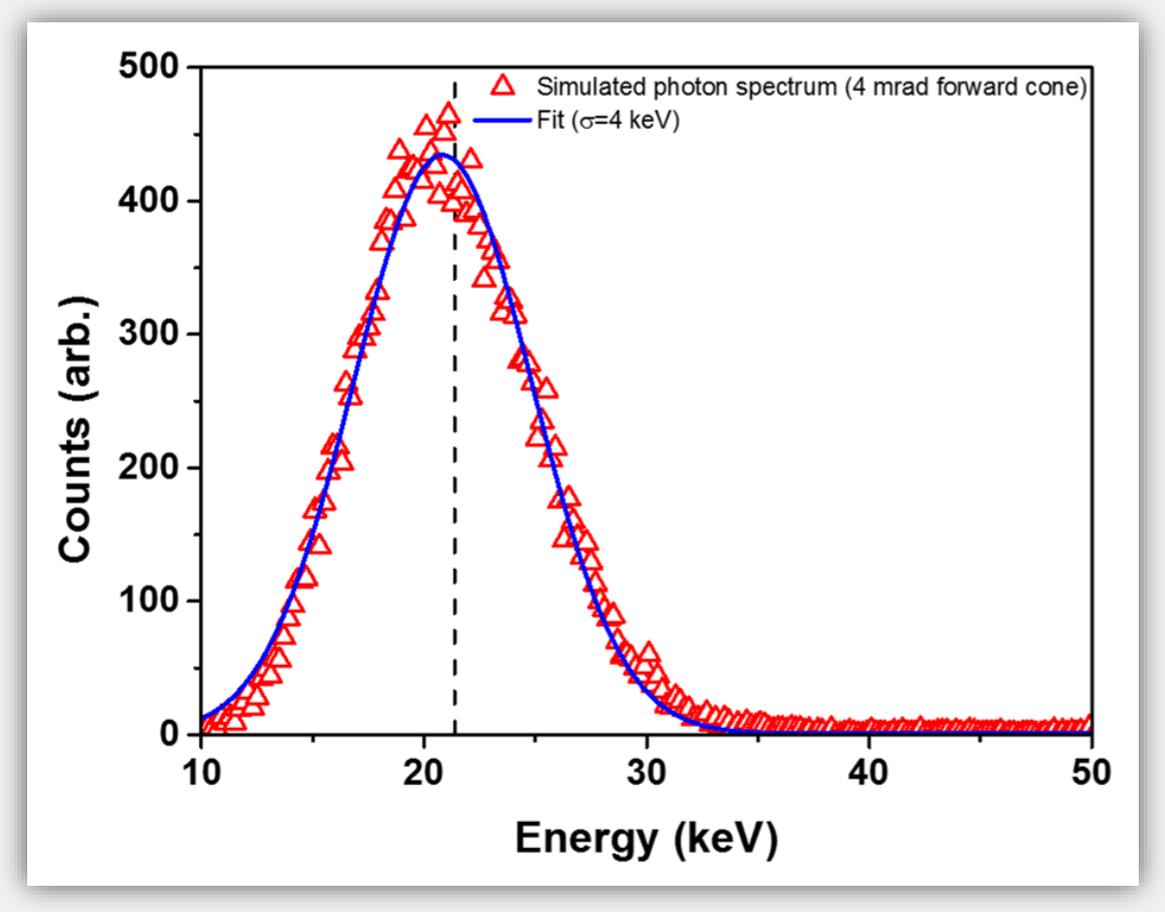
X-ray profile 1 m from the source (1 cm size)



Beam divergence is small (~ mrad) except at the lowest x-ray energy



Photon number can be scaled to synchrotron levels using latest lasers



Narrowband spectrum on-axis which can be spectrally purified using optics.

- $>10^{10}$ photons s^{-1} (1% BW) with current parameters and will meet the requirements for metrology and SAXS.
- Improvement to electron accelerator and optimization will improve performance by 10X or more

Conclusions

All optical Inverse Compton Scattering Source has the following features:

- ☐ **Tunable energy**
- ☐ **Small spot size**
- ☐ **High repetition rate**
- ☐ **High brightness**
- ☐ **Narrowband x-rays**
- ☐ **Laboratory Size**

CD-SAXS Requirements	Values	Synchrotron (Brookhaven)	Classic RAG	Mo or Cu Kα (rotating anode)	ICS (Diocles)
Photon Number (Ph/s)	10^8 (high-K)-10^{10} (Si+photo resist)	5 x 10^{12} @ 10 keV	10^9 ph/s	10^6 ph/s	10^{10} (1%BW) @ 20-50 keV
Energy	> 20 keV tunable	5-30		17.45 keV	8-100 keV
Bandwidth %	< 2%	.01			1 %
Beam size	< 100 μm^{1,2}	20 um	380 um		5-10 μm
Time per measurement	< 1 min^{1,2}				
Divergence/angular spread	< 0.5^{2}	60 μrad		300 μrad	5 mrad (20 keV)
Laboratory Size		21 km²			< 50 m²

- **All-optical Inverse Compton scattering source is a contender for new generation small-angle x-ray scattering sources**
- **ICS university based sources could be the first of its kind for SAXS, USAXS, WAXS nanometrology research**

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